Numerical Prediction of Meteoric Infrasound Signatures

Marian Nemec

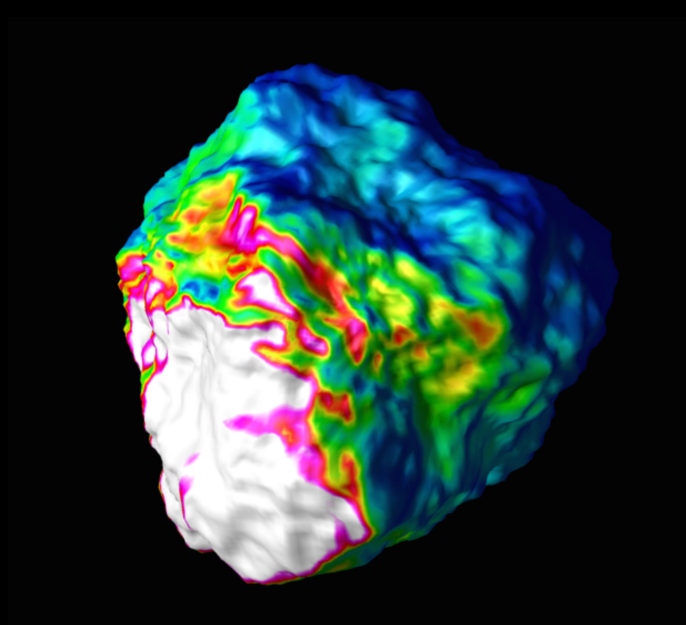
Science & Technology Corp.
NASA Ames, USA

Michael Aftosmis

NASA Ames Research Center
USA

Peter Brown

University of Western Ontario
Canada



Meteoroids 2016

Noordwijk, June 8, 2016

Motivation and Objectives

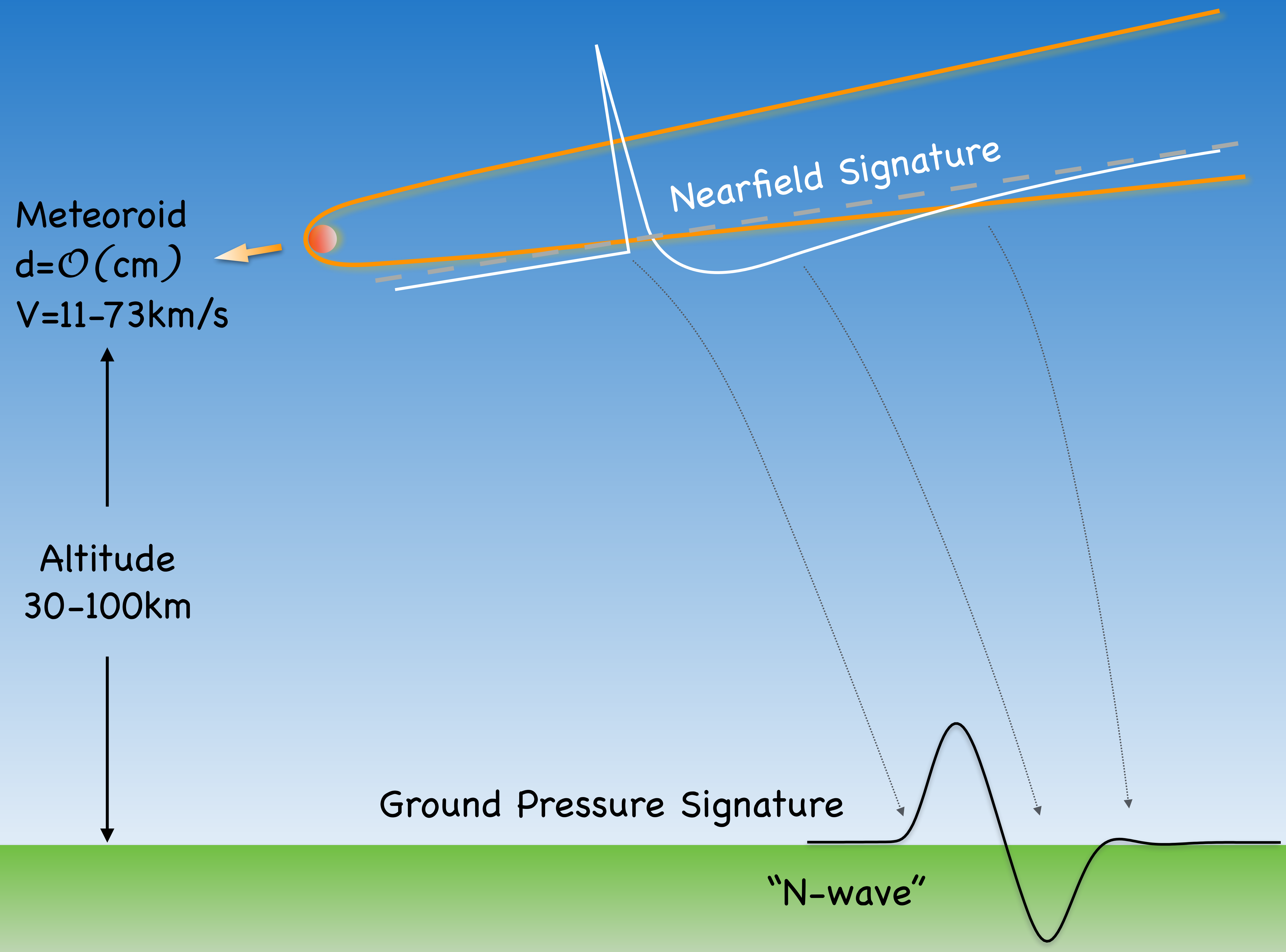
- Meteors: steady source of infrasound
  - Meteoroid speed: 11-73 km/s
  - Meteoroid size: mm - m’s
  - Strong bow-shock and complex flowfield

- New constrained regional dataset
  - Over 80 infrasound signatures collected by the Southern Ontario Meteor Network (SOMN), *Silber 2014*

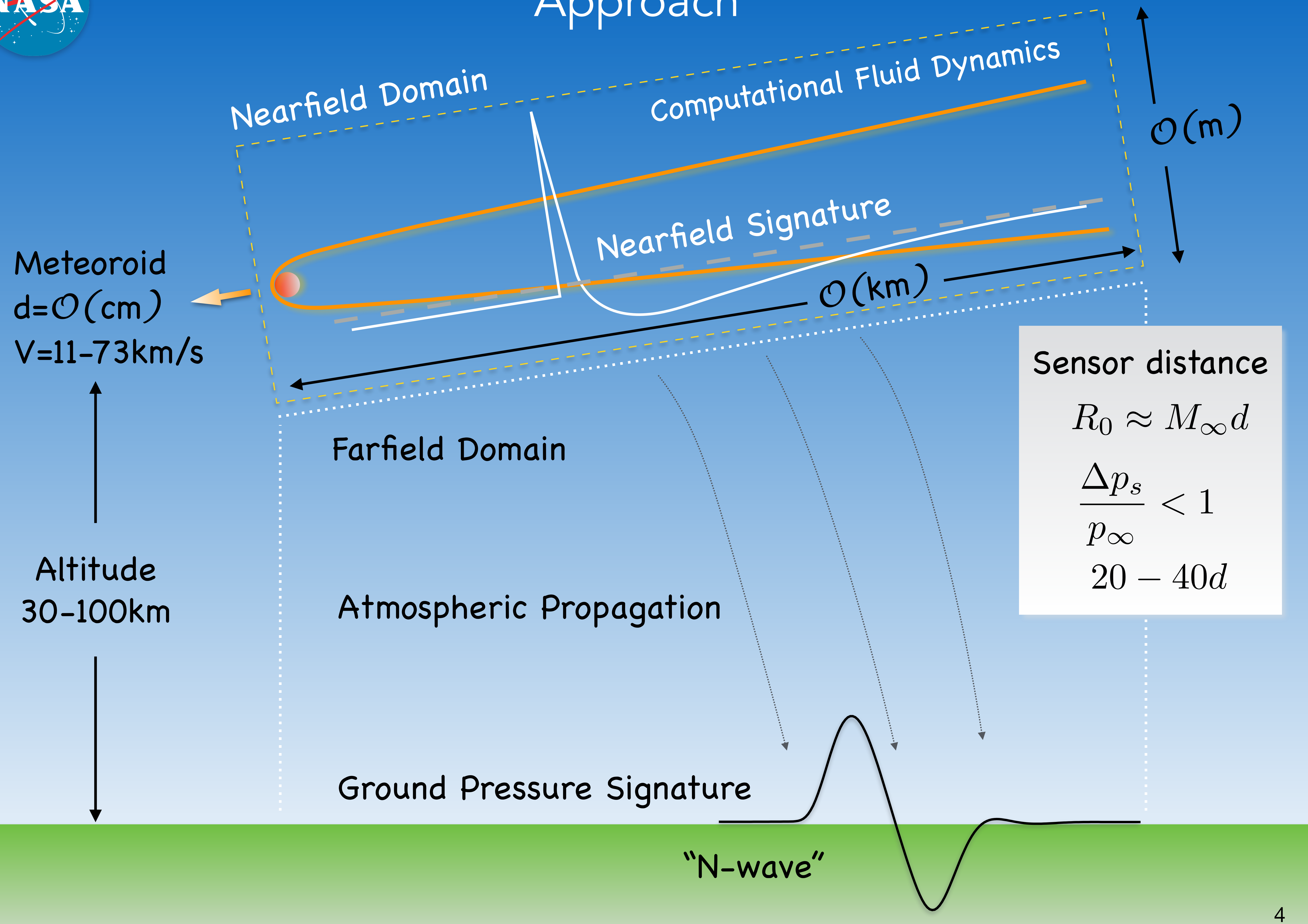
- Infrasound-based mass estimates verify optical and radar observations
  - Bow-shock essentially independent of ablation process
  - Analytic model (*ReVelle 1976*): significant variability in predicting infrasonic mass

- How accurate are numerical models? How can they help?
  - Promising simulations of *Henneton et al. 2015*
  - Relax assumptions required to formulate analytic models

Approach


Meteoroid
d=$\mathcal{O}$(cm)
V=11-73km/s
Altitude
30-100km
Nearfield Signature
Ground Pressure Signature
"N-wave"

Approach



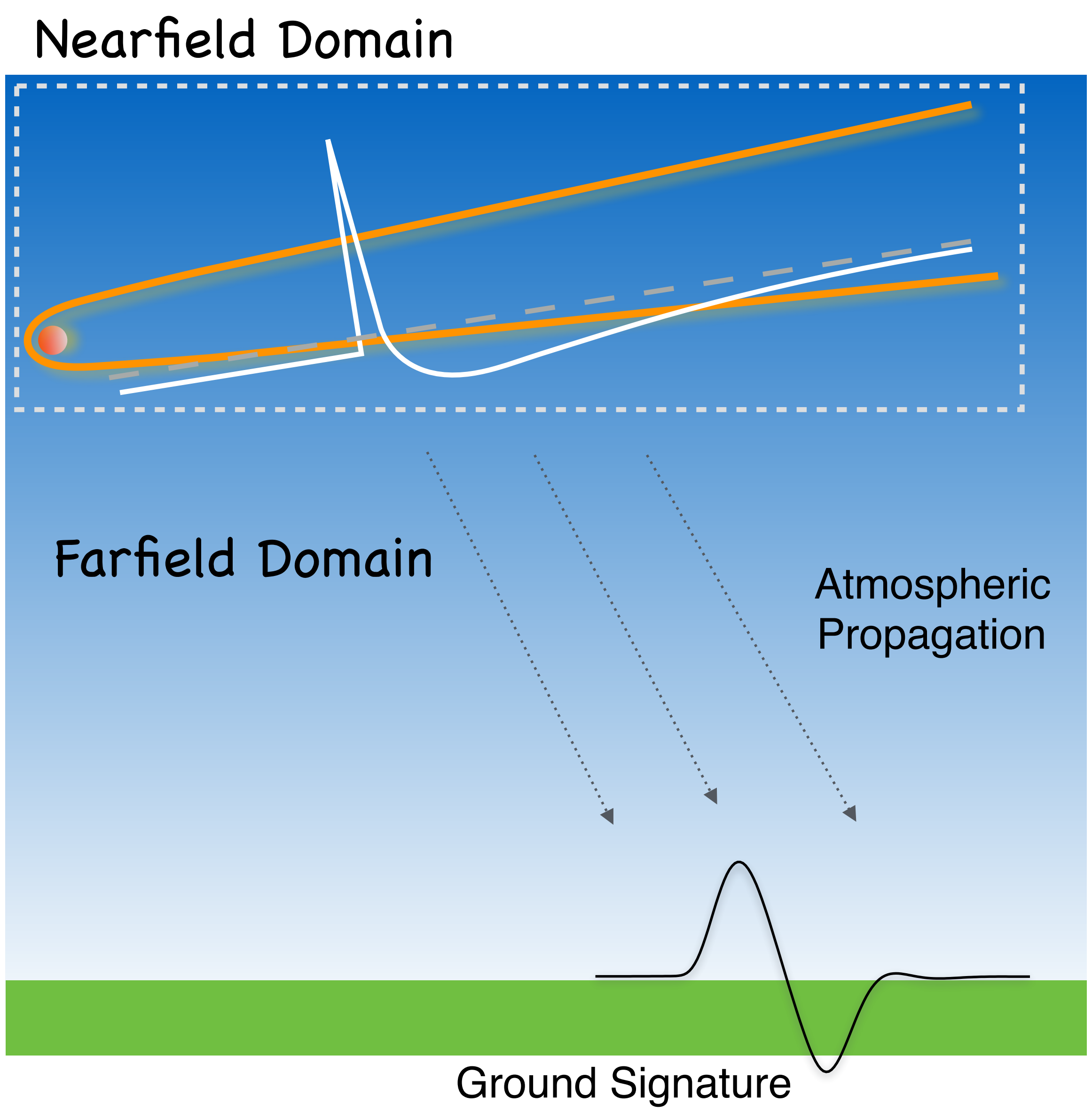
Sensor distance

$$R_0 \approx M_\infty d$$

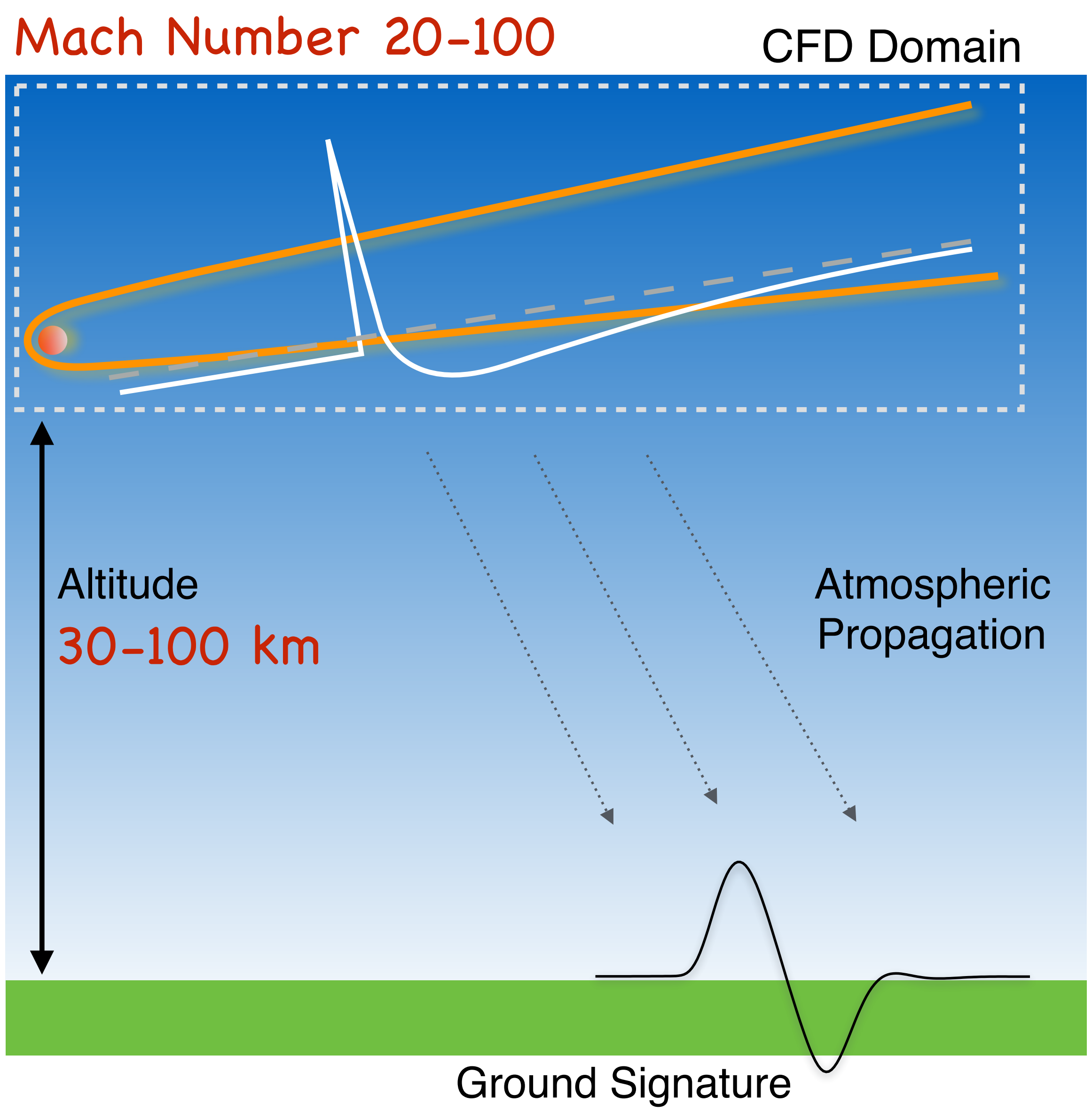
$$\frac{\Delta p_s}{p_\infty} < 1$$

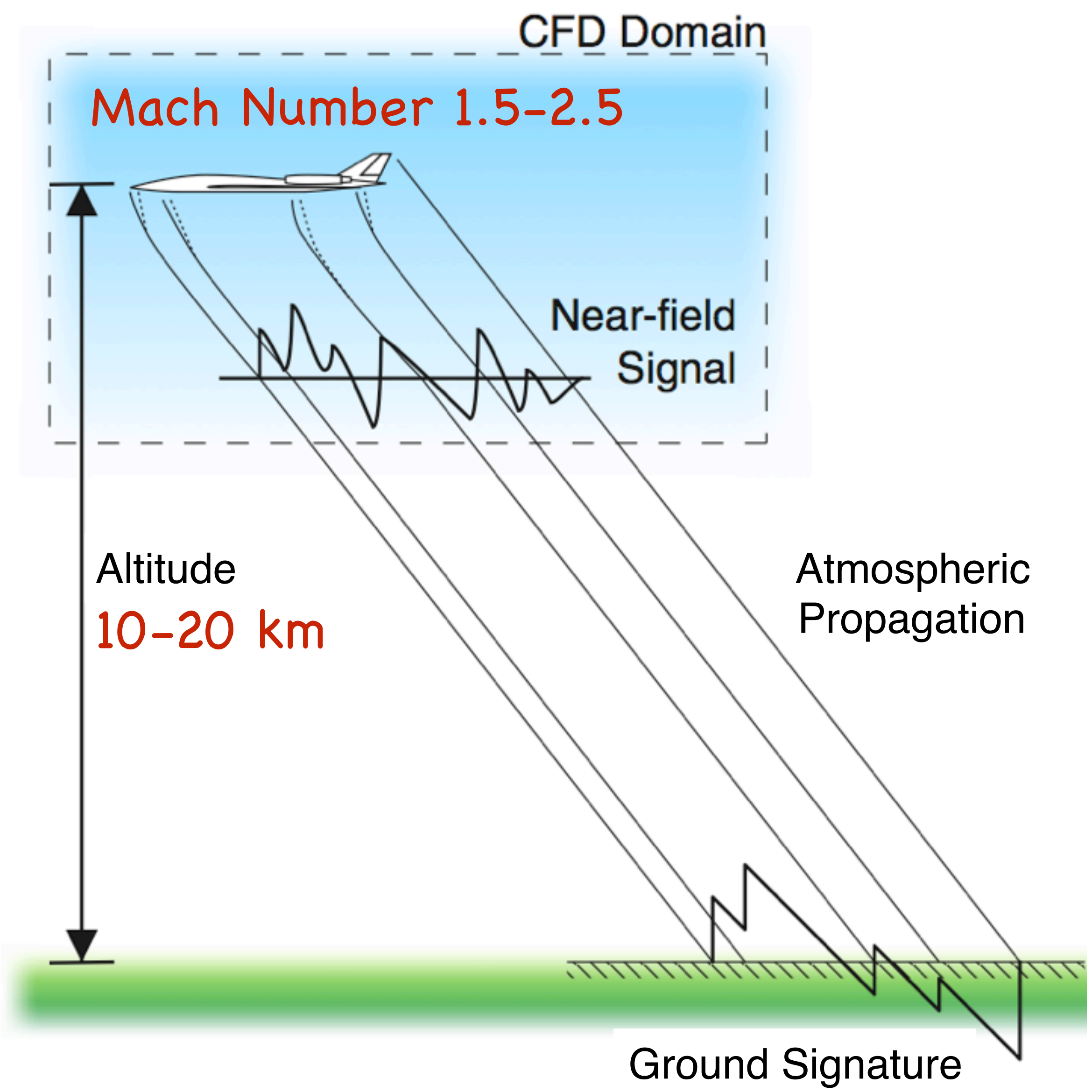
$$20 - 40d$$

Approach


Nearfield Domain
Farfield Domain
Atmospheric
Propagation
Ground Signature

Approach





Typical overpressure < 1 Pa

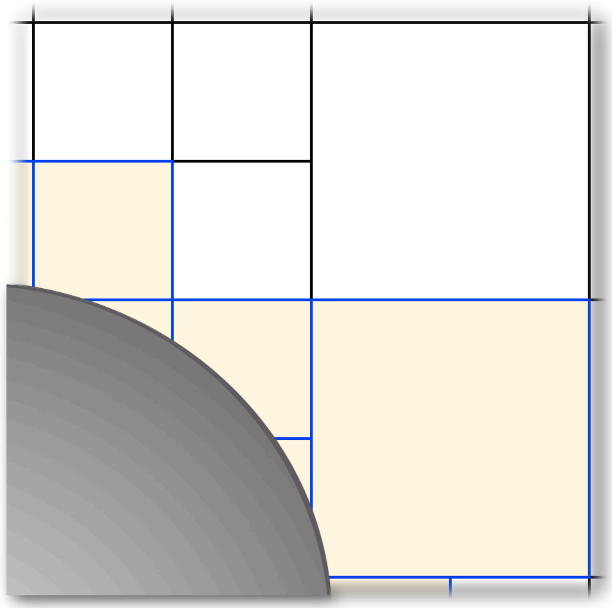
Typical overpressure > 10 Pa

Leverage tools and experience from aircraft sonic-boom analysis and low-boom design

Nearfield Solver: Cart3D

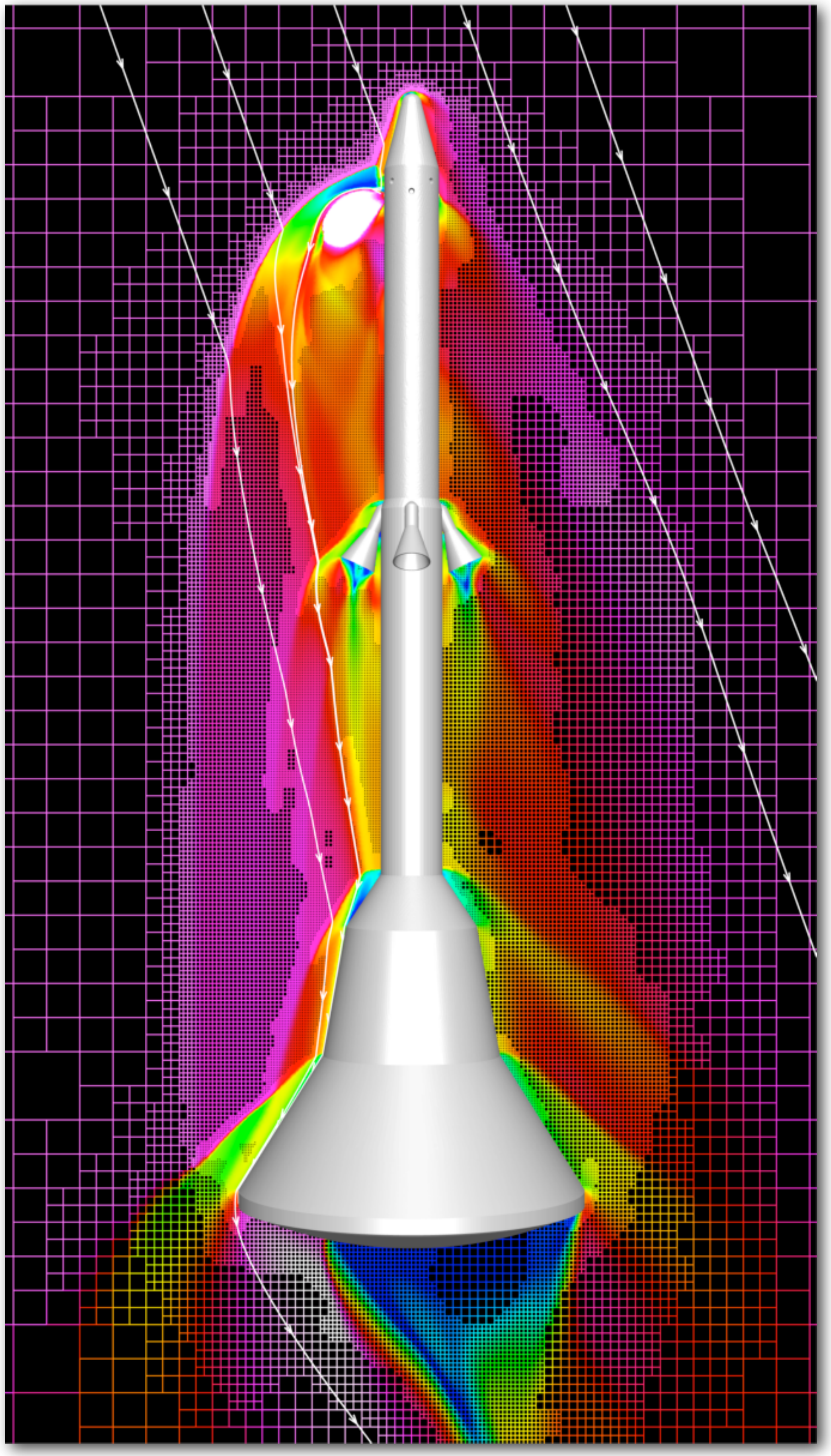
Assumptions

- Air in thermochemical equilibrium
- Steady inviscid flow
  - Euler equations



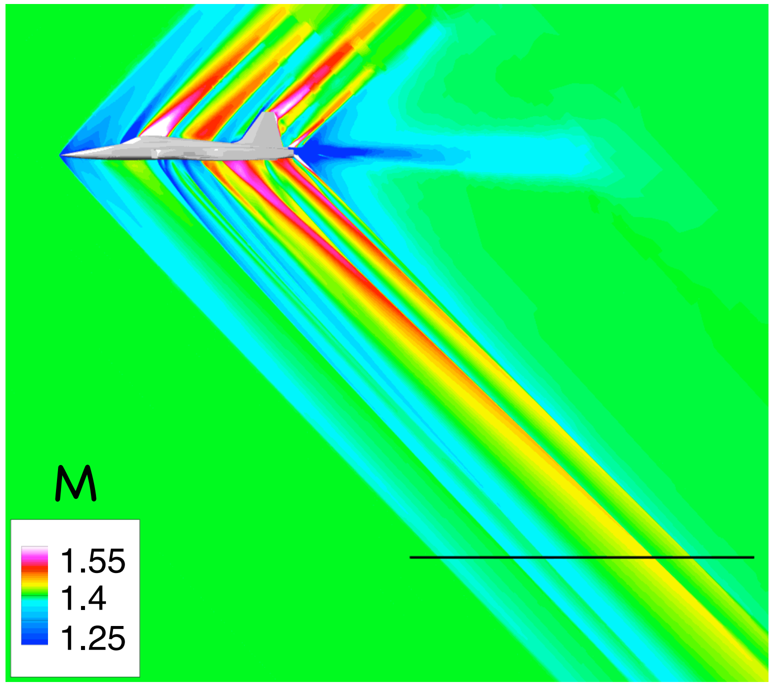
Flow Simulation

- Cartesian mesh with cut cells
- Second-order finite-volume spatial discretization
- Adaptive mesh refinement
  - Method of adjoint weighted residuals: mesh tailored to minimize discretization error in selected outputs
- Broad use throughout NASA, US Government, industry and academia



www.nas.nasa.gov/publications/software/docs/cart3d

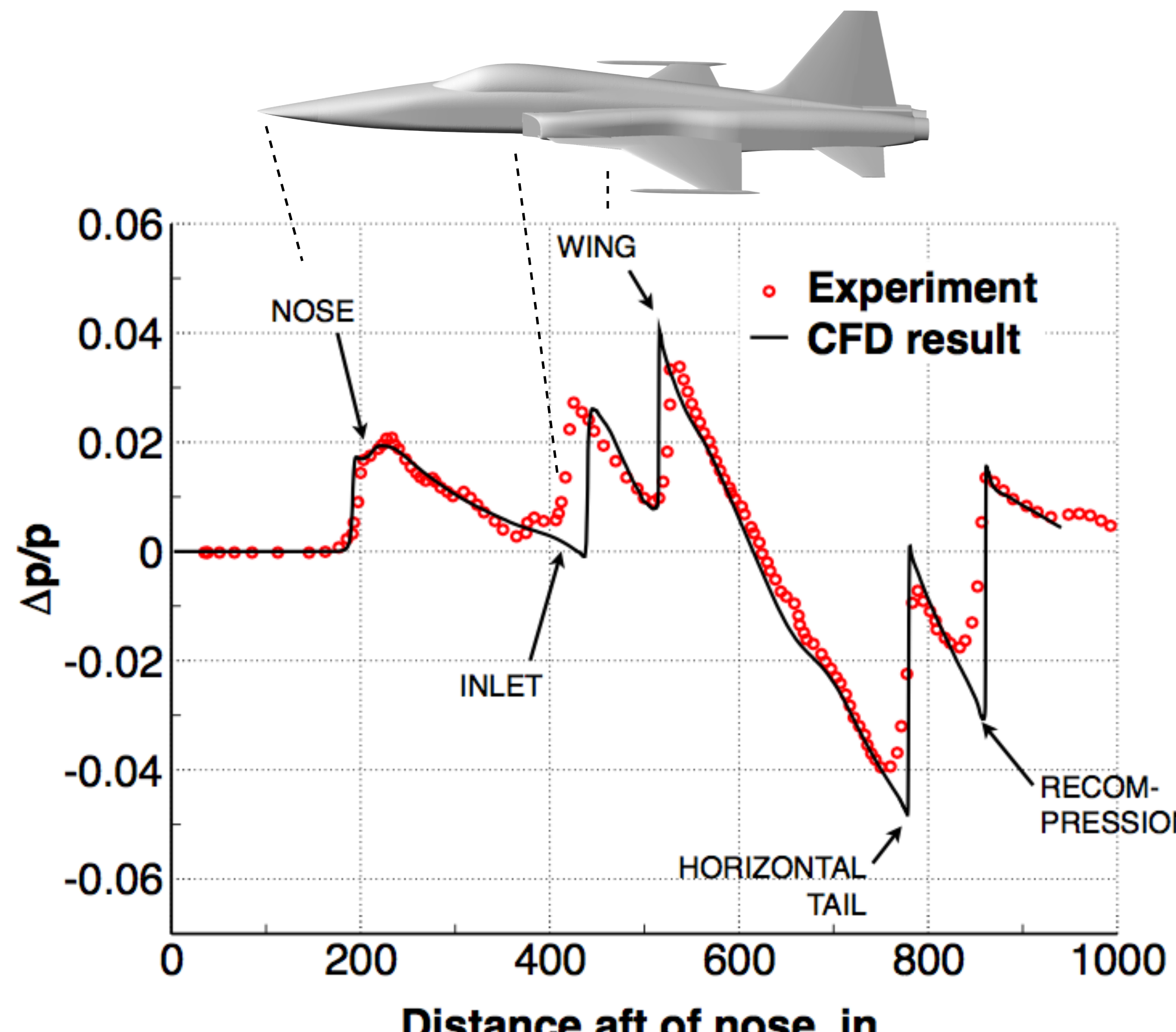
Nearfield Signature Prediction with Cart3D



F5-E Nearfield Pressure Flight Test

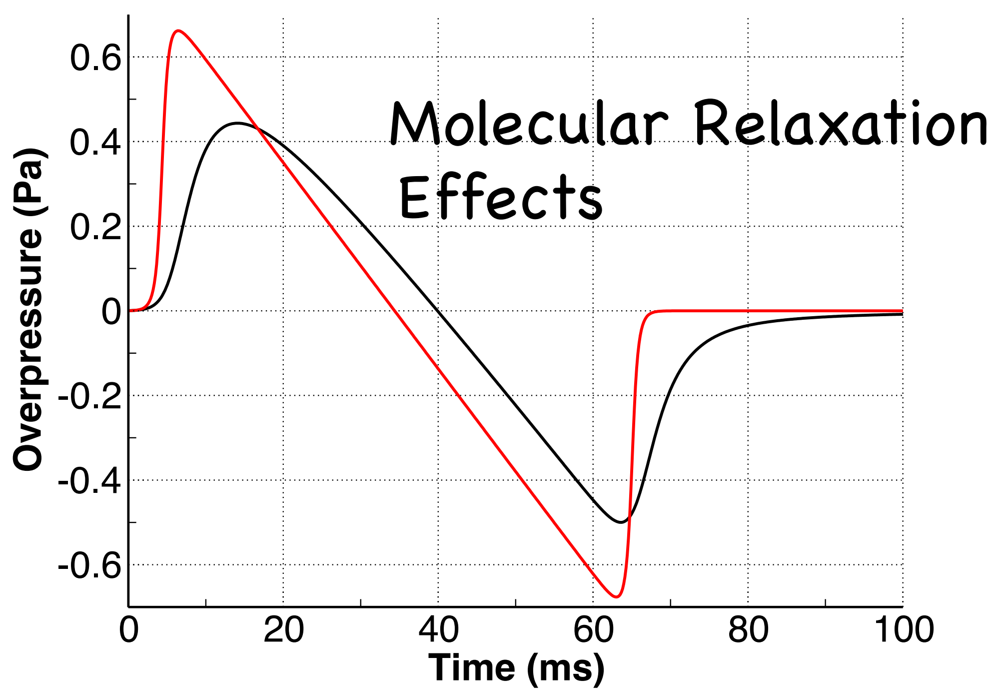
Output of interest: $J = \int_0^L \left(\frac{\Delta p}{p_\infty}\right)^2 ds$

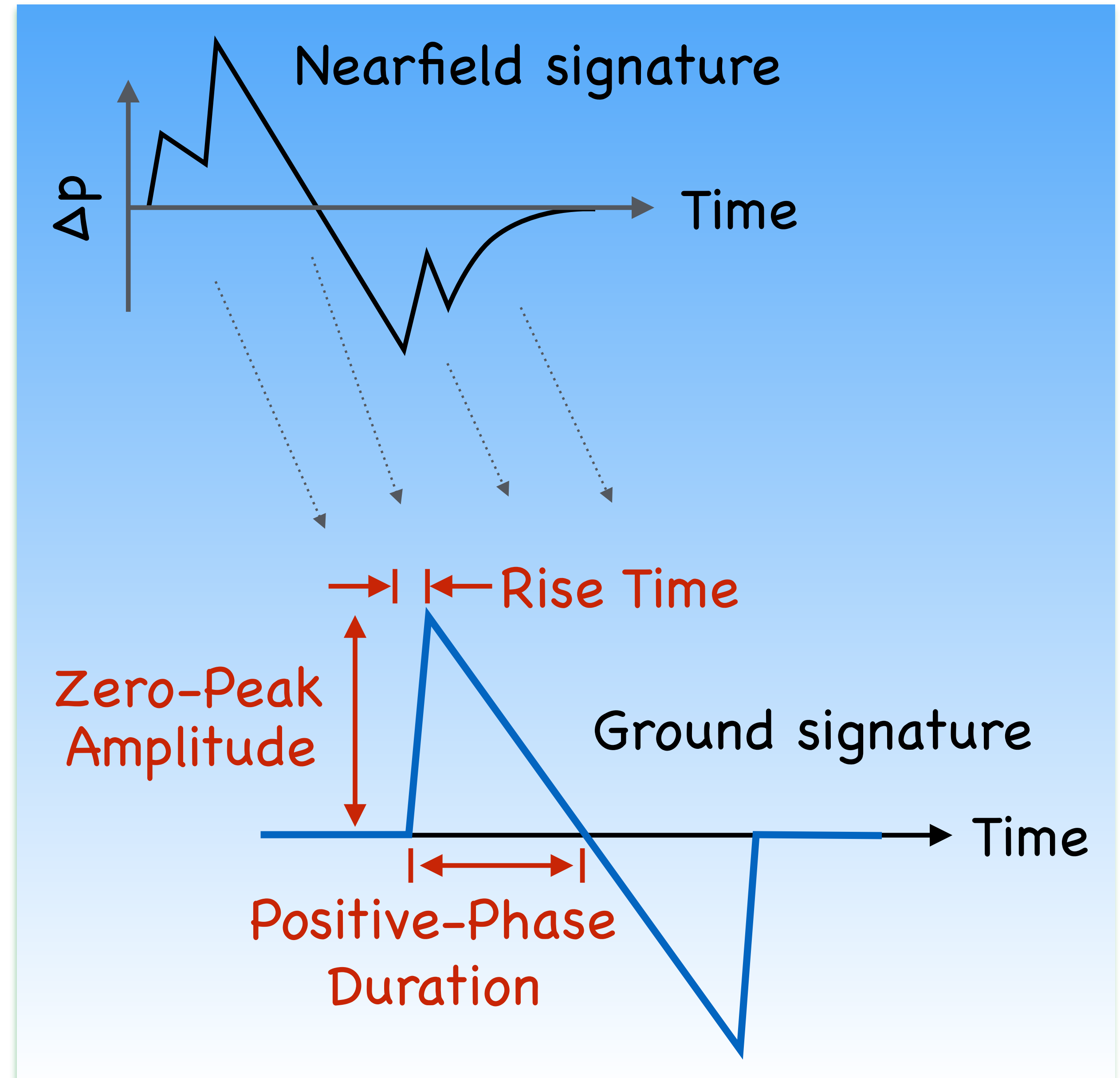
- Mach number (M) 1.4
- Separation distance is roughly 2 aircraft lengths



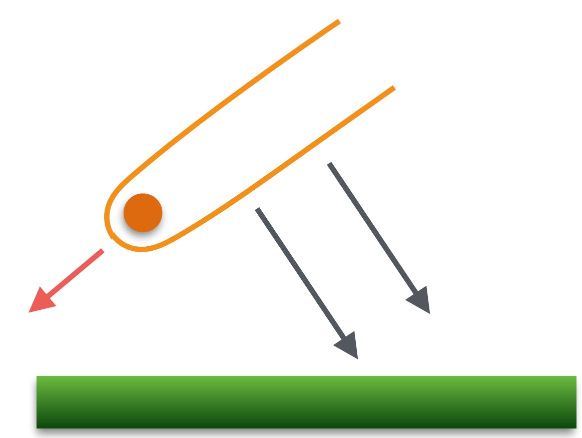
Farfield Signal Propagation: sBOOM

- Augmented Burgers equation
  - Nonlinear steepening
  - Thermoviscous absorption
  - Molecular relaxation





- User specified temperature, wind and humidity profiles
- Ray tracing via geometric acoustics
- Primary signature only (no secondary reflections)



Rallabhandi, J. Aircraft, 2011

Results

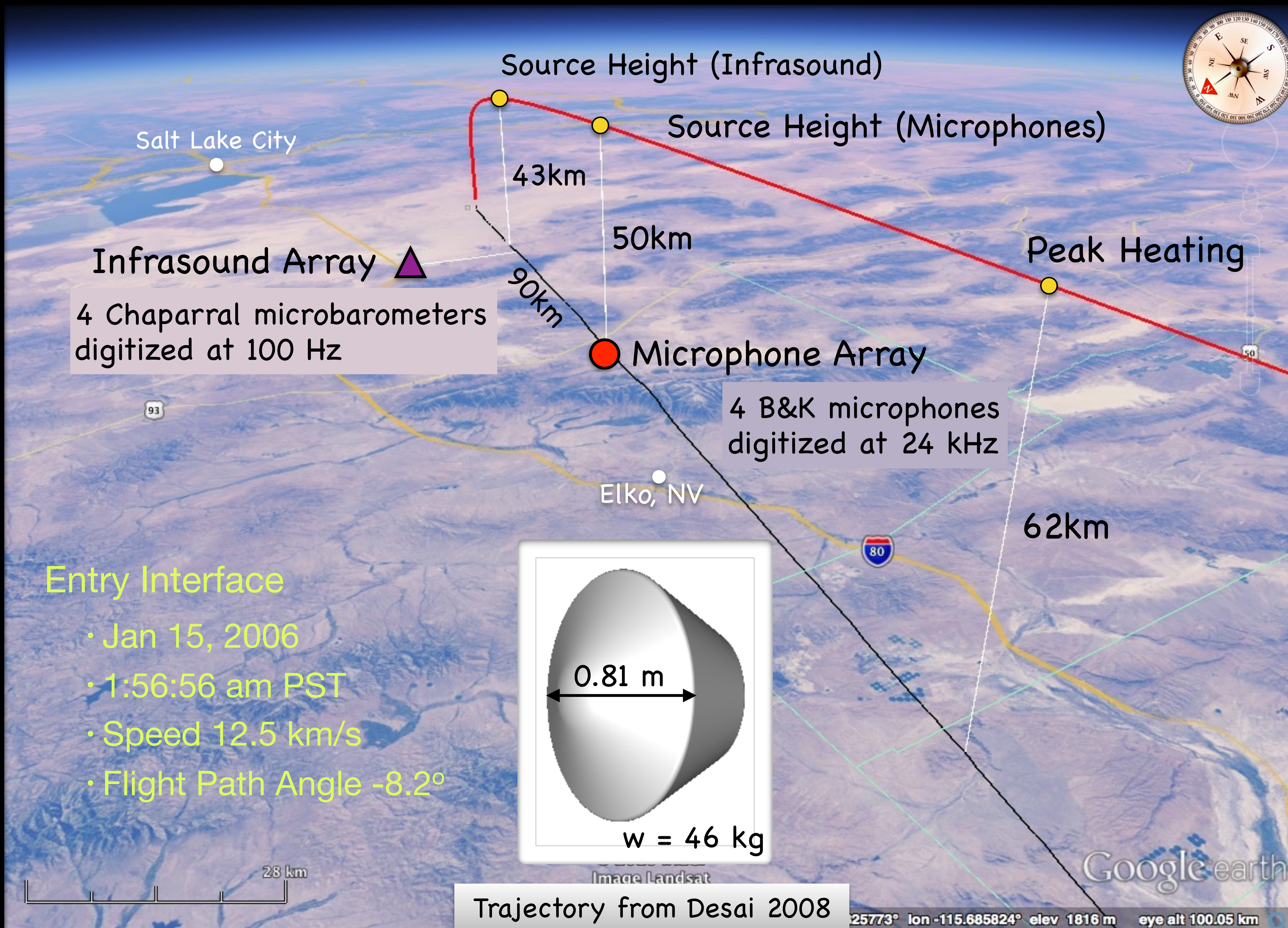
Part A. Stardust Entry

- Artificial meteor (12.5 km/s)
- Well-defined geometry and trajectory
- Multiple pressure-signature records

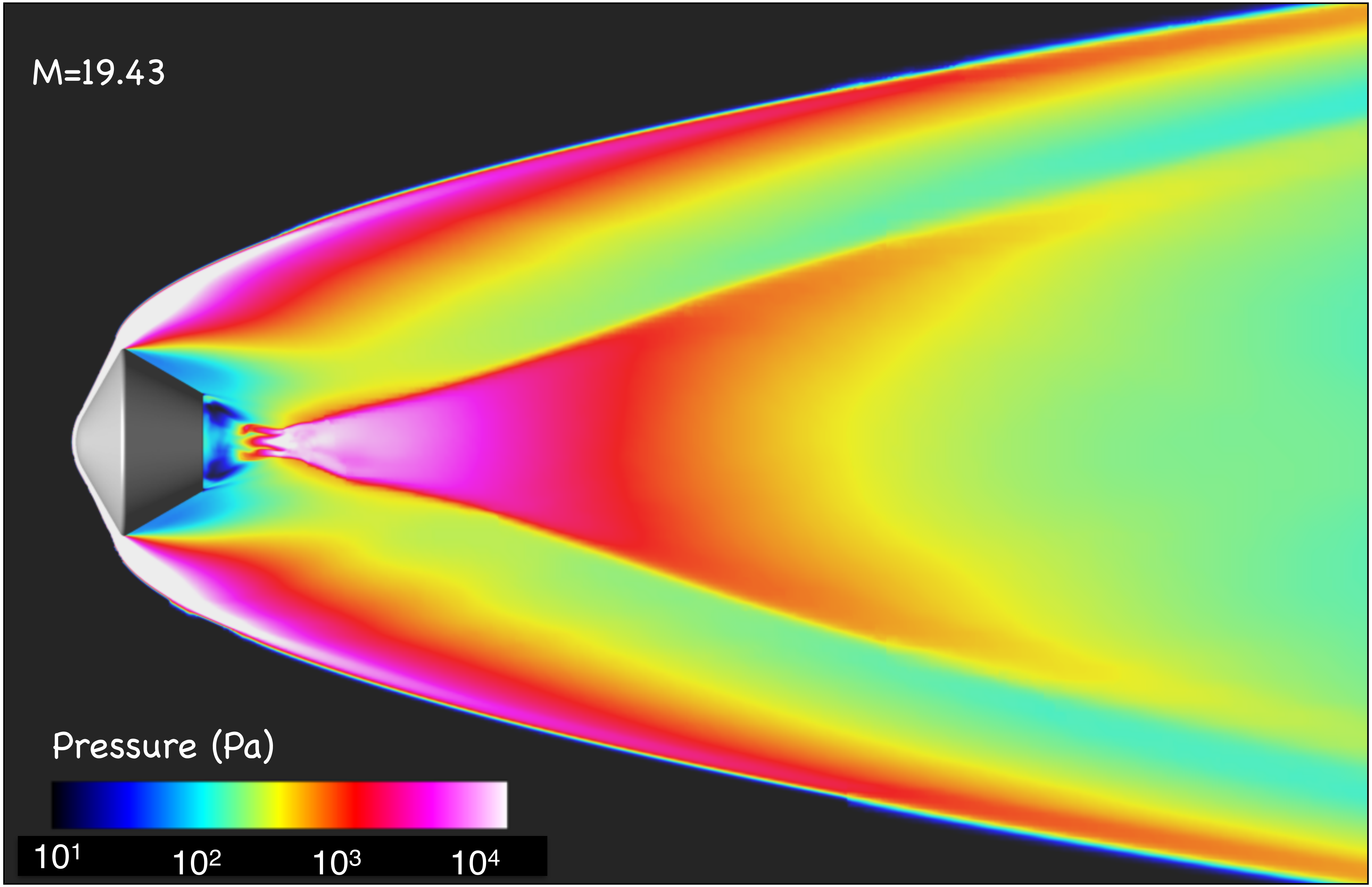
Part B. SOMN Infrasound Dataset

1. Meteor 20081028
    - Single infrasonic arrival
2. Meteor 20090428
    - Multiple arrivals
    - Steeper and faster entry

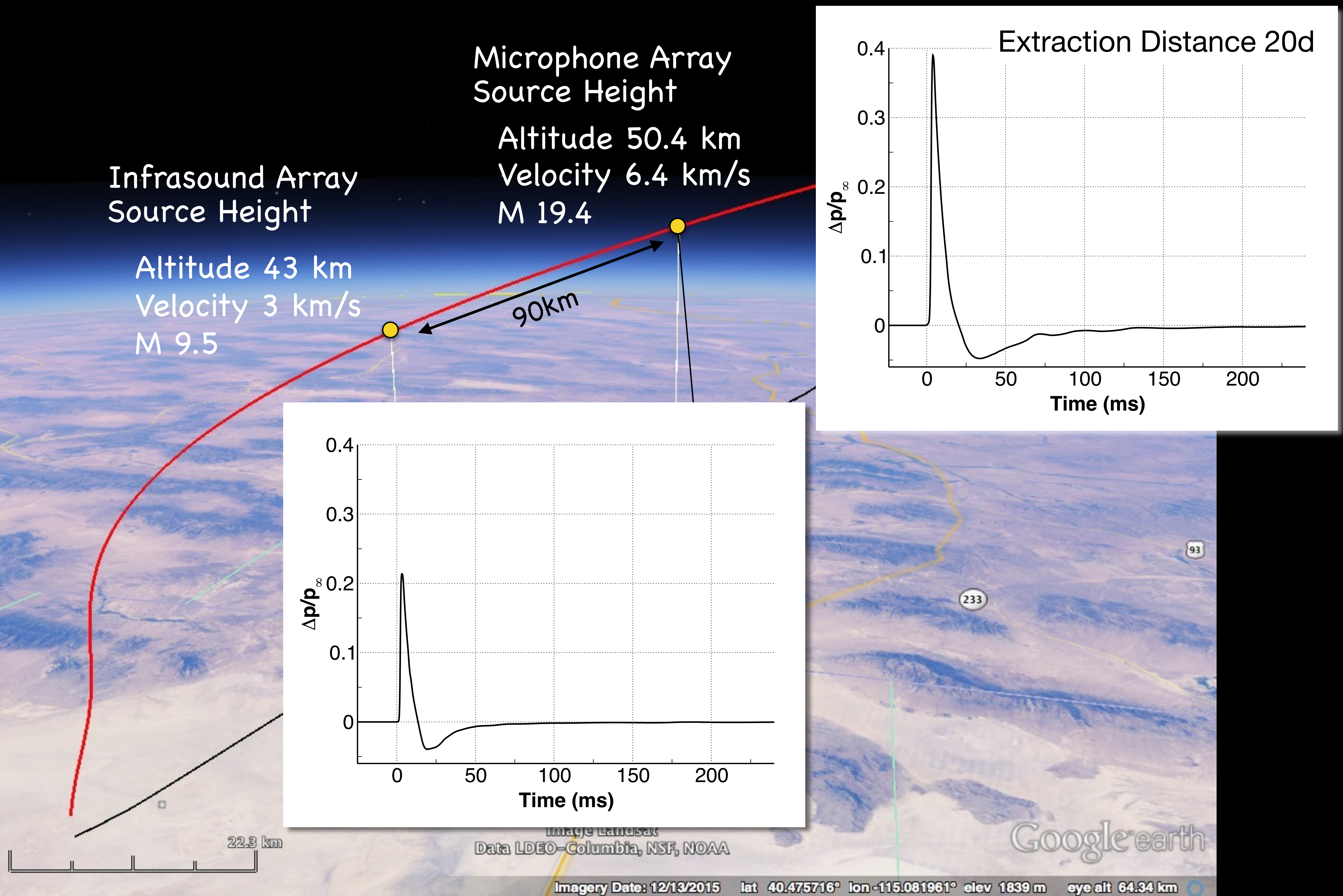
Stardust — Artificial Meteor



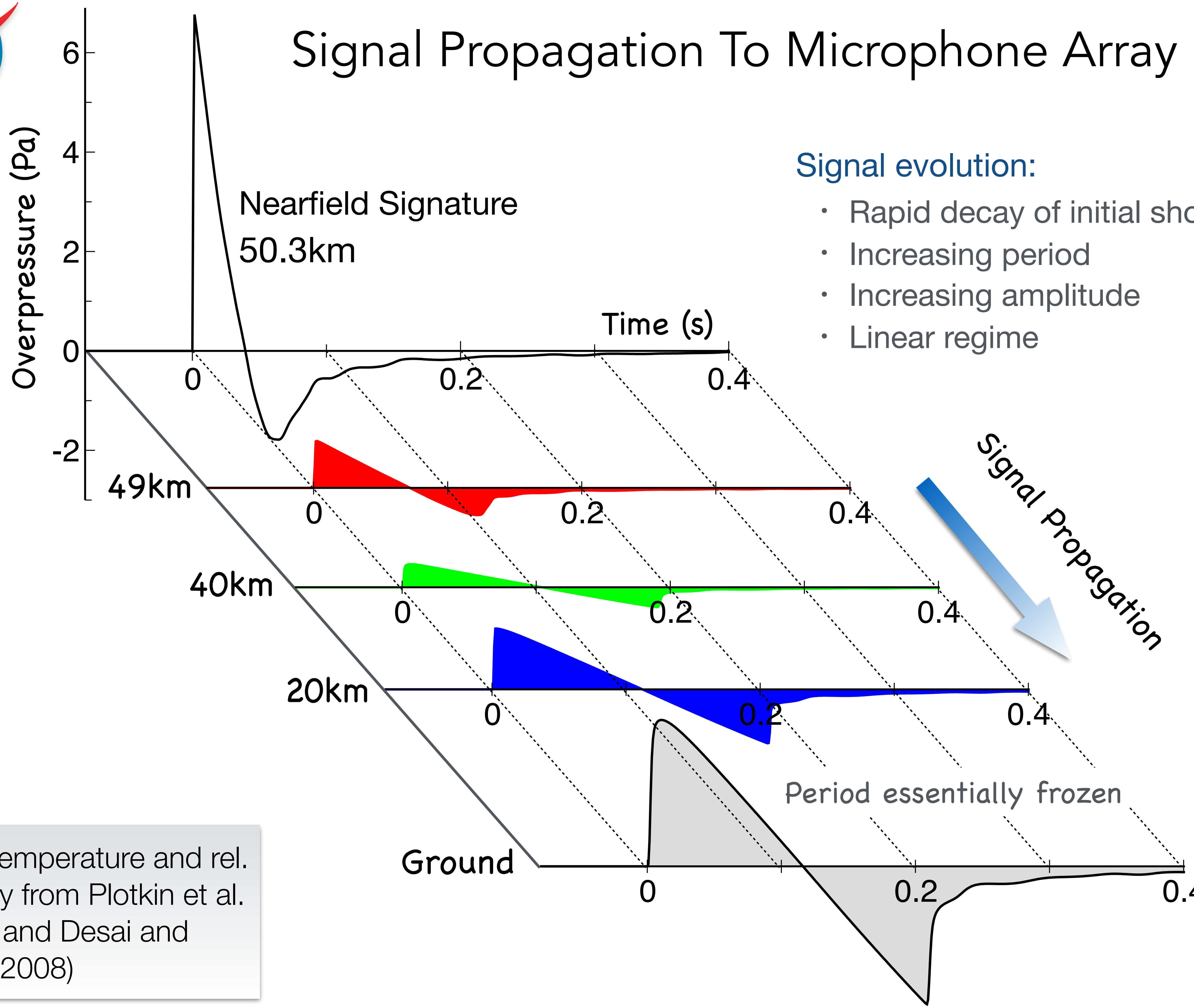
Nearfield Pressure



Nearfield Signatures



Signal Propagation To Microphone Array

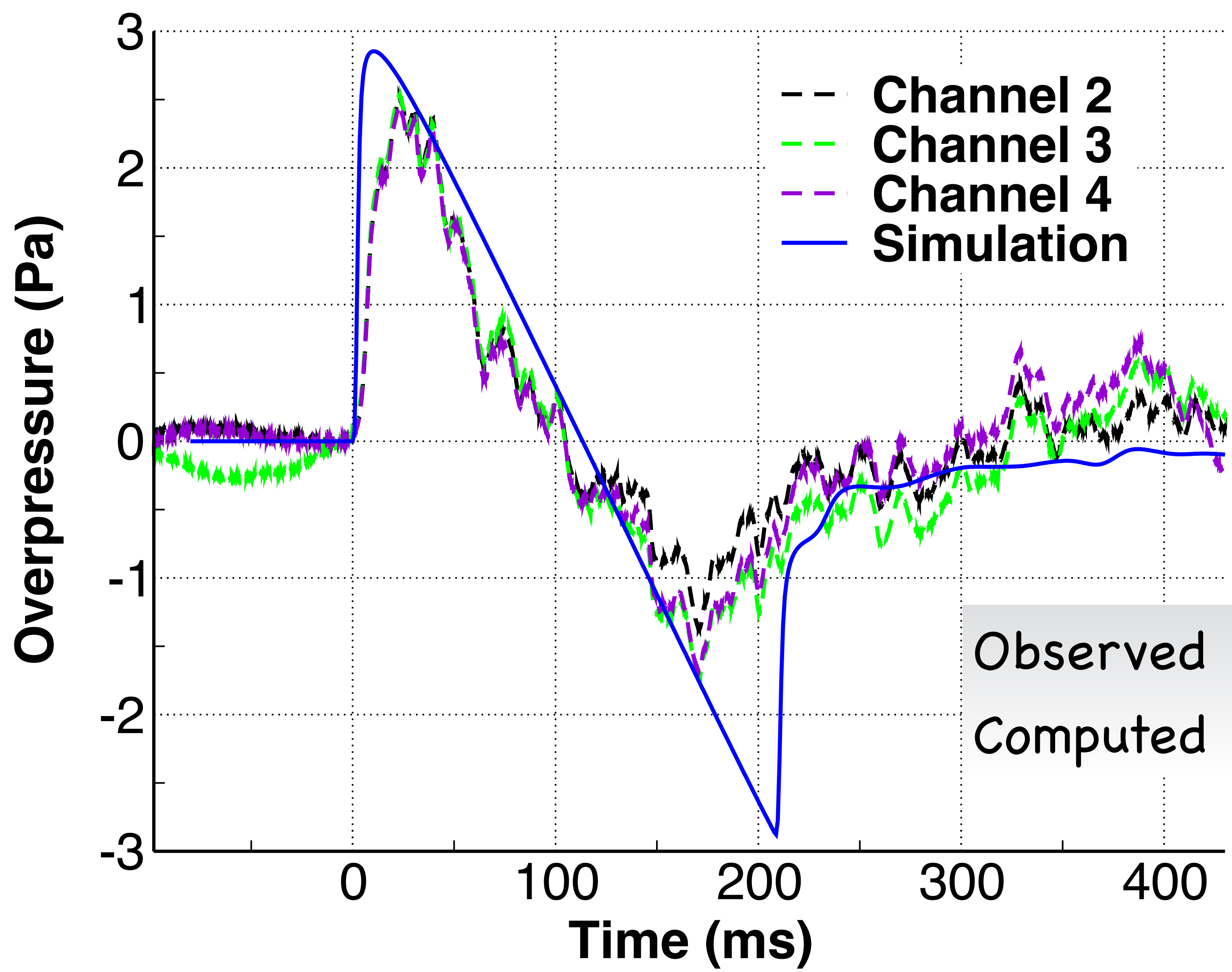


Signal evolution:

- Rapid decay of initial shock
- Increasing period
- Increasing amplitude
- Linear regime

Wind, temperature and rel. humidity from Plotkin et al. (2006), and Desai and Qualls (2008)

Microphone Array Comparison



M 19.4

Speed 6.4 km/s

Off-track 4°

Altitude 50.4 km

Observed travel time: 161 s

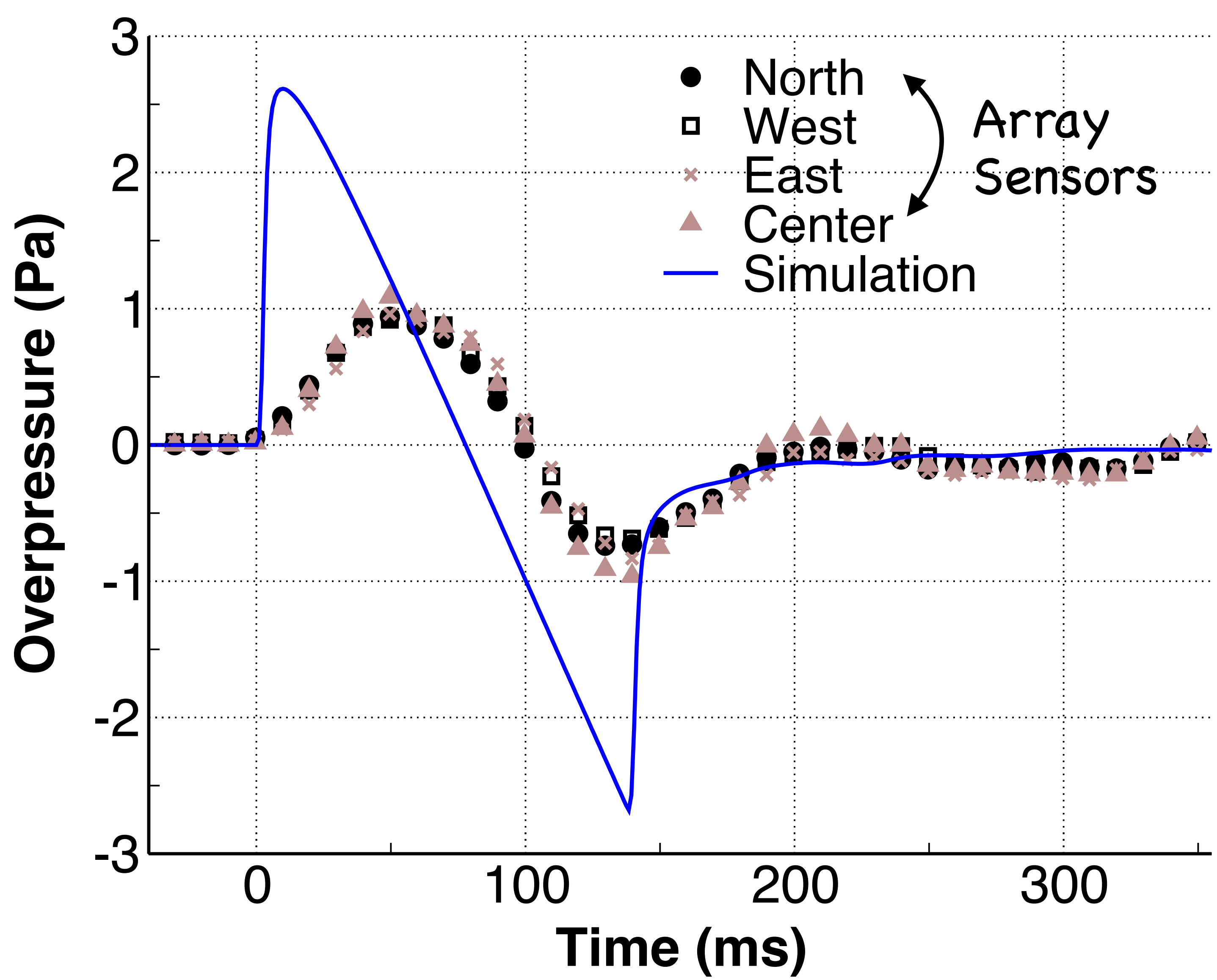
Computed travel time: 162.6 s

- Excellent prediction of period and amplitude
- Measured signature more asymmetric (expansion not as deep)

Data: Plotkin et al. (2006)

Atmospheric conditions: Plotkin et al. (2006), Desai and Qualls (2008) and ReVelle and Edwards (2007)

Infrasound Array Comparison



M 9.5

Speed 3 km/s

Off-track 38°

Altitude 43 km

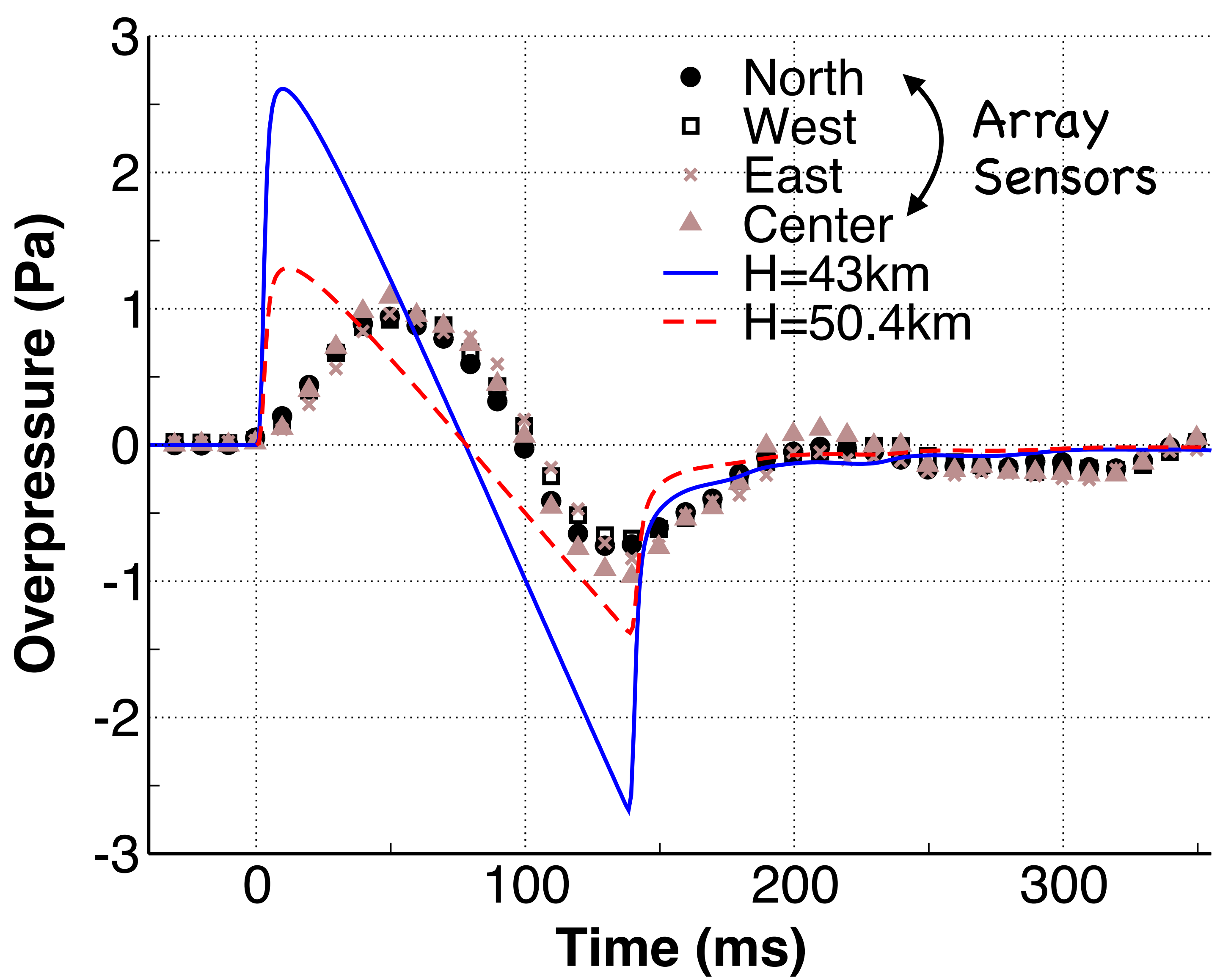
- Observations show much longer rise time and lower amplitude
- Some agreement on slope in expansion region

Data: ReVelle and Edwards (2007)

Atmospheric conditions: Plotkin et al. (2006), Desai and Qualls (2008) and ReVelle and Edwards (2007)

Effect of Source Height

Infrasound Array Location



M 9.5

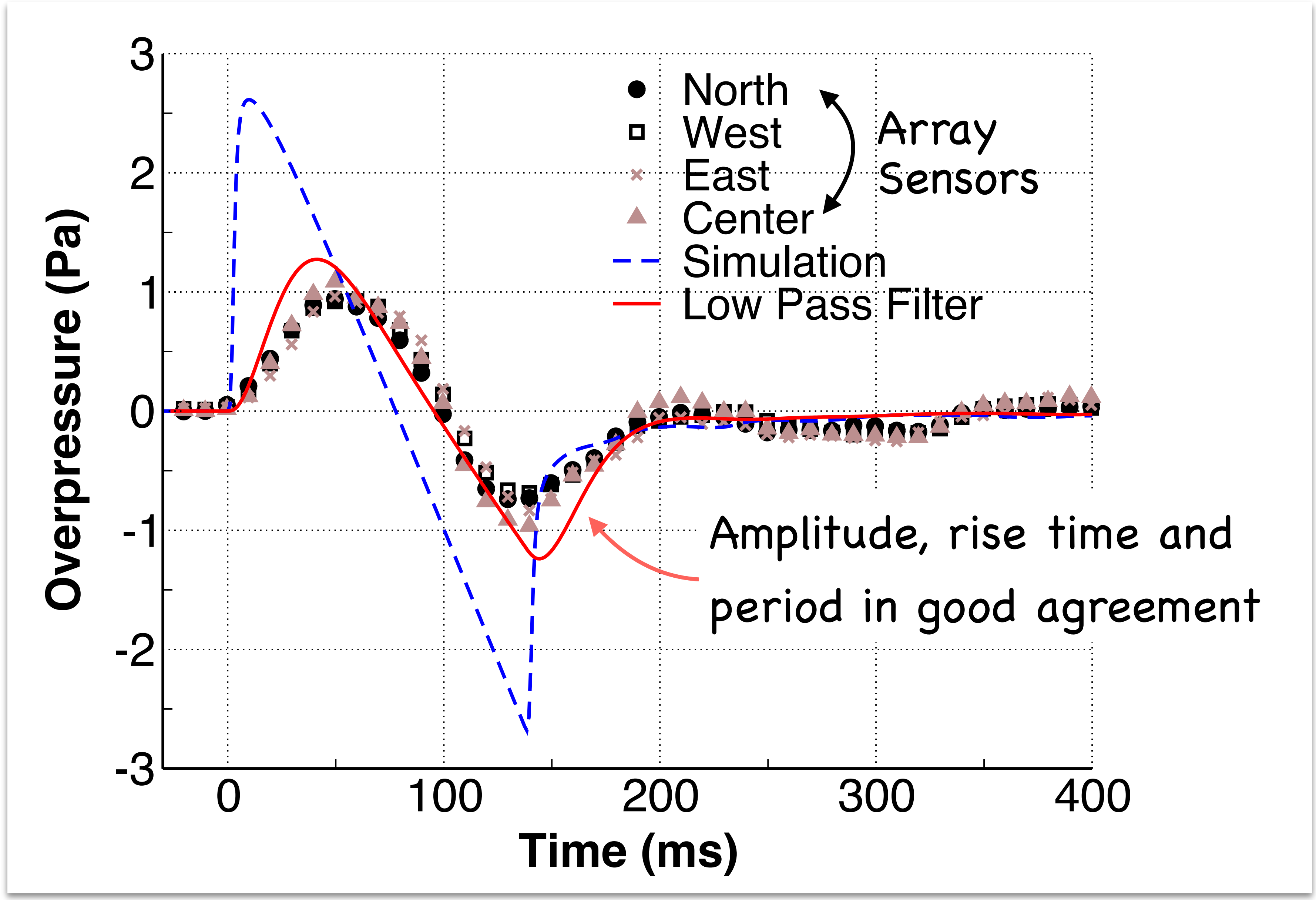
Speed 3 km/s

Off-track 38°

Altitude 43 km

- To achieve correct signal attenuation requires unrealistic source height
- Rise time remains inaccurate

Account for Array Local Response



- Microbarometer: flat response to 200 Hz
- Digital sample rate 100 Hz
- Porous, 16 m long, soaker hoses
- Attenuate amplitude (0.6x) and filter with second-order Butterworth low-pass filter (15Hz)

Results

Part A. Stardust Entry

- Artificial meteor (12.5 km/s)
- Well-defined geometry and trajectory
- Multiple infrasound records

Part B. SOMN Infrasound Dataset

1. Meteor 20081028
    - Single infrasonic arrival
    - Low entry angle at 15.8 km/s
2. Meteor 20090428
    - Multiple arrivals
    - Steeper and faster entry

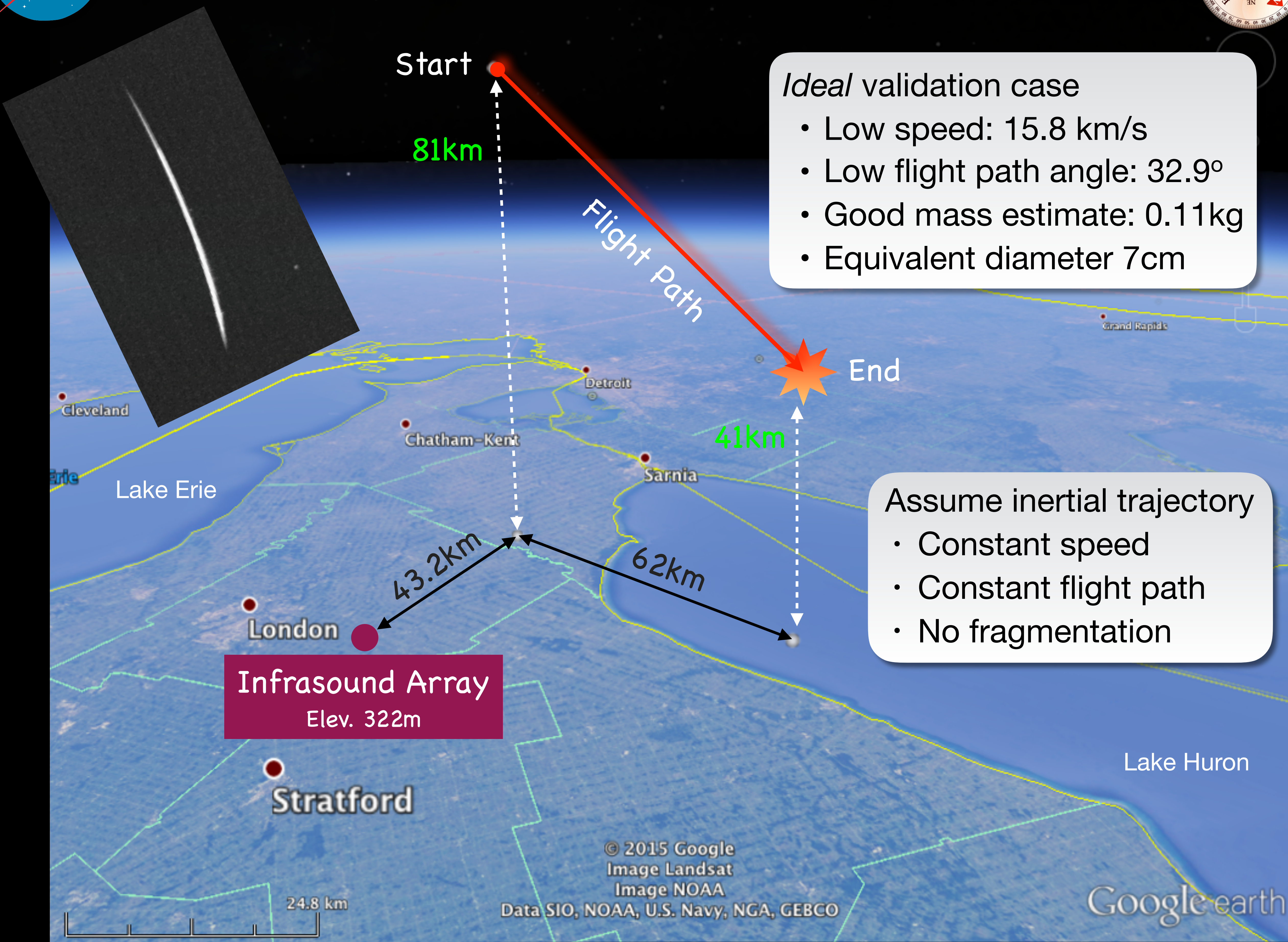
Meteor 20081028 Photometry Data

Ideal validation case

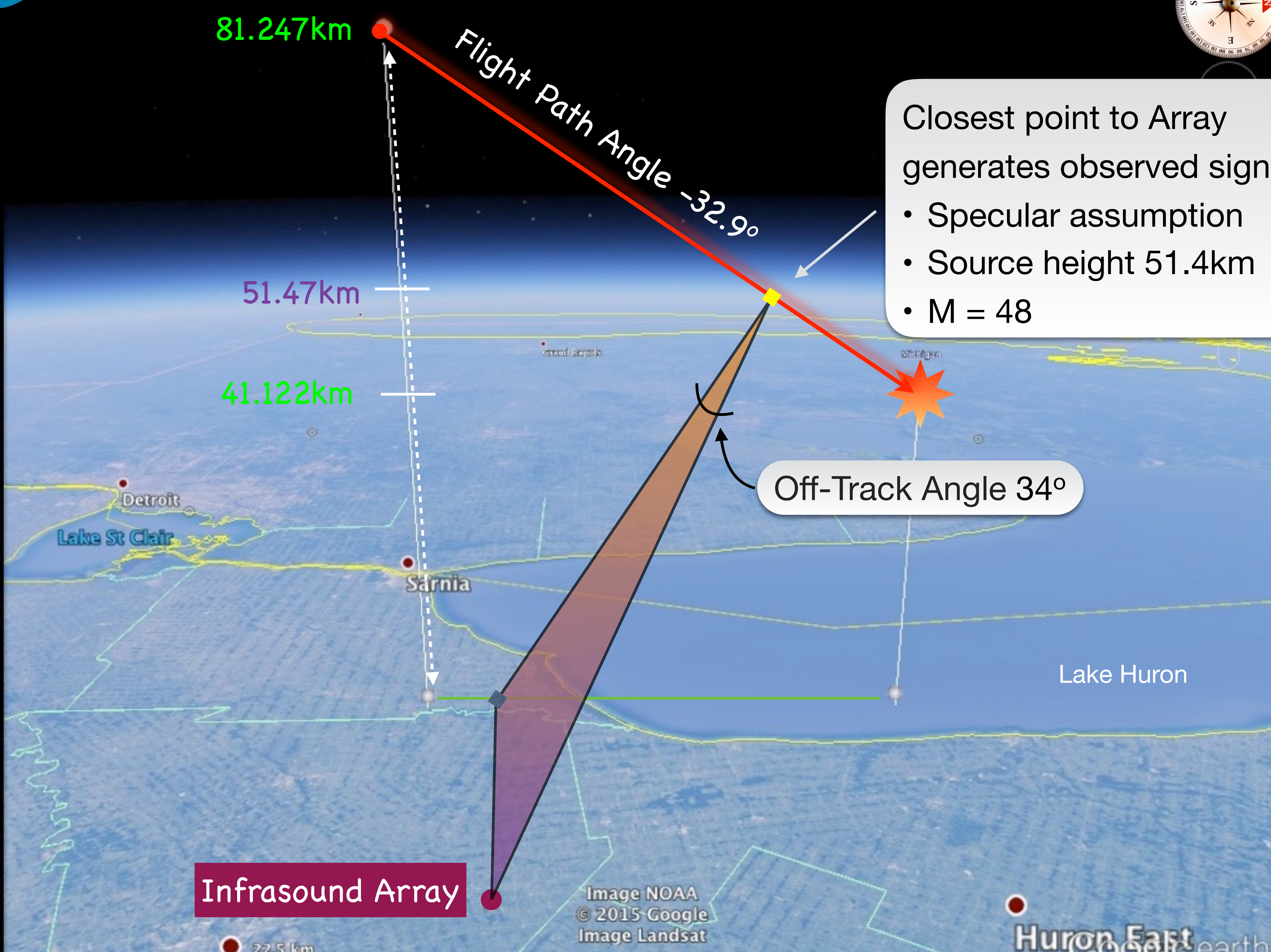
- Low speed: 15.8 km/s
- Low flight path angle: 32.9°
- Good mass estimate: 0.11kg
- Equivalent diameter 7cm

Assume inertial trajectory

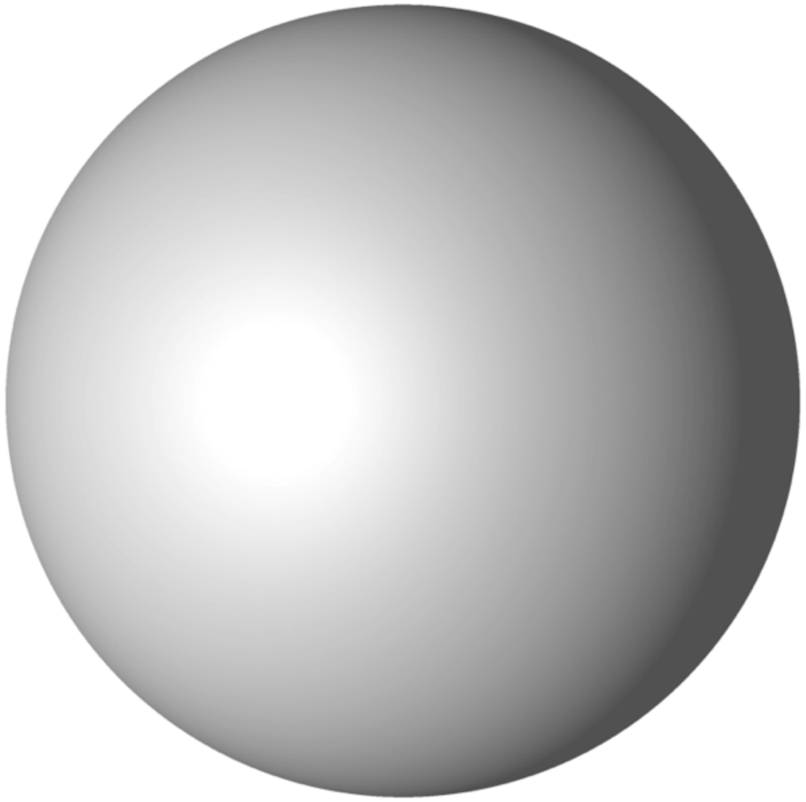
- Constant speed
- Constant flight path
- No fragmentation



Trajectory Overview and Source Height

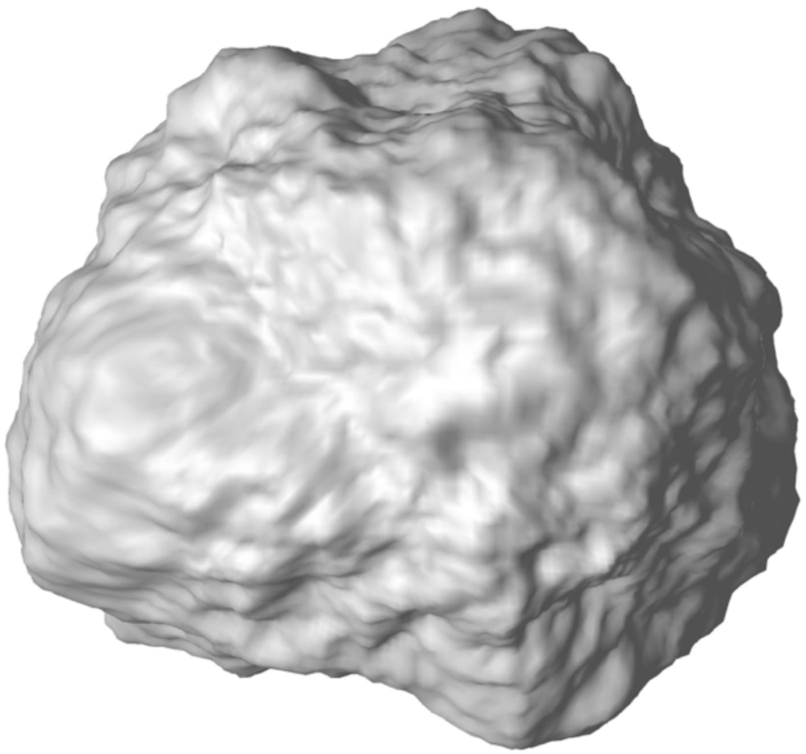


Meteoroid Geometry



d = 0.07 m

"Sphere"

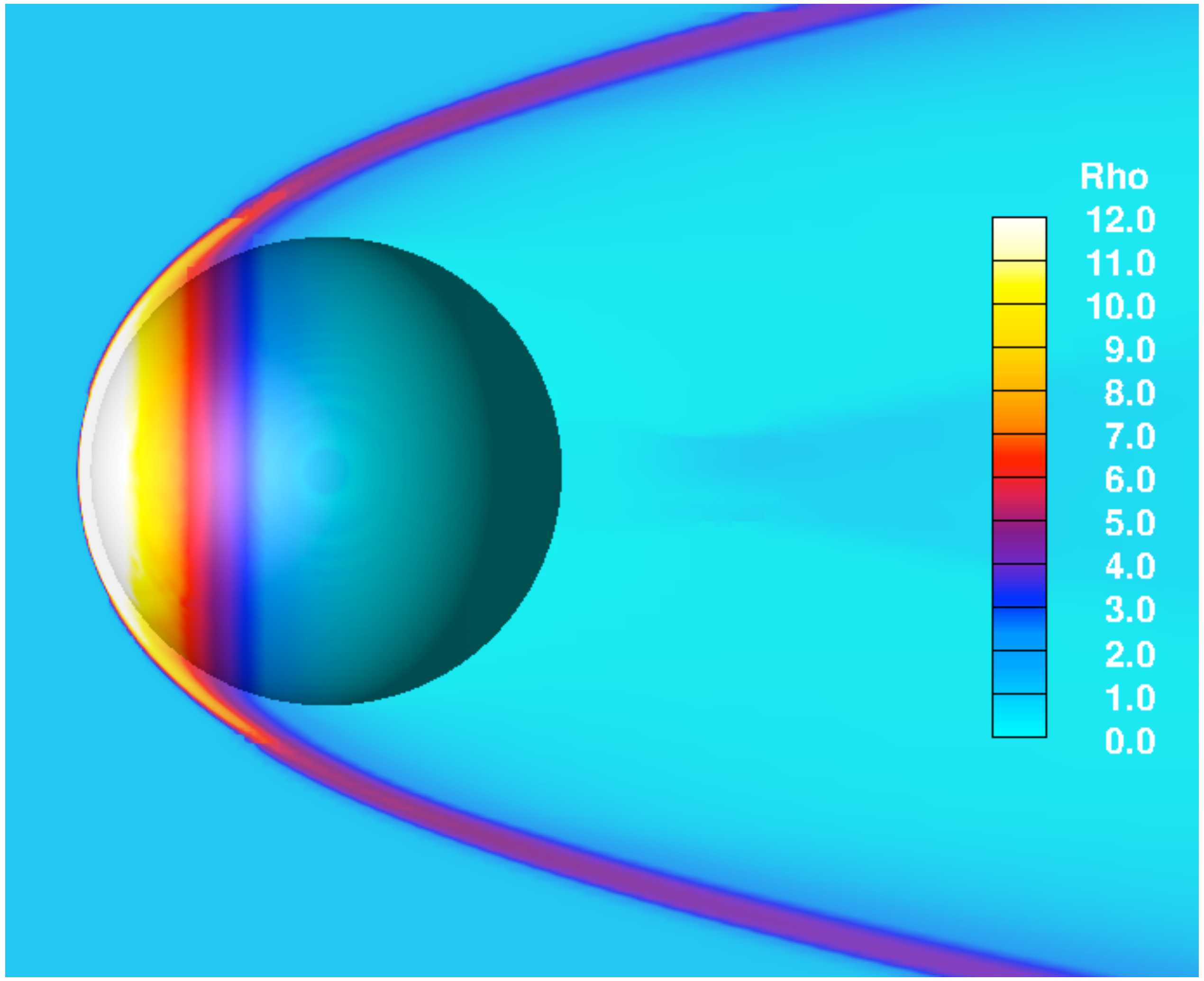


d = 0.07 m

"Rock"

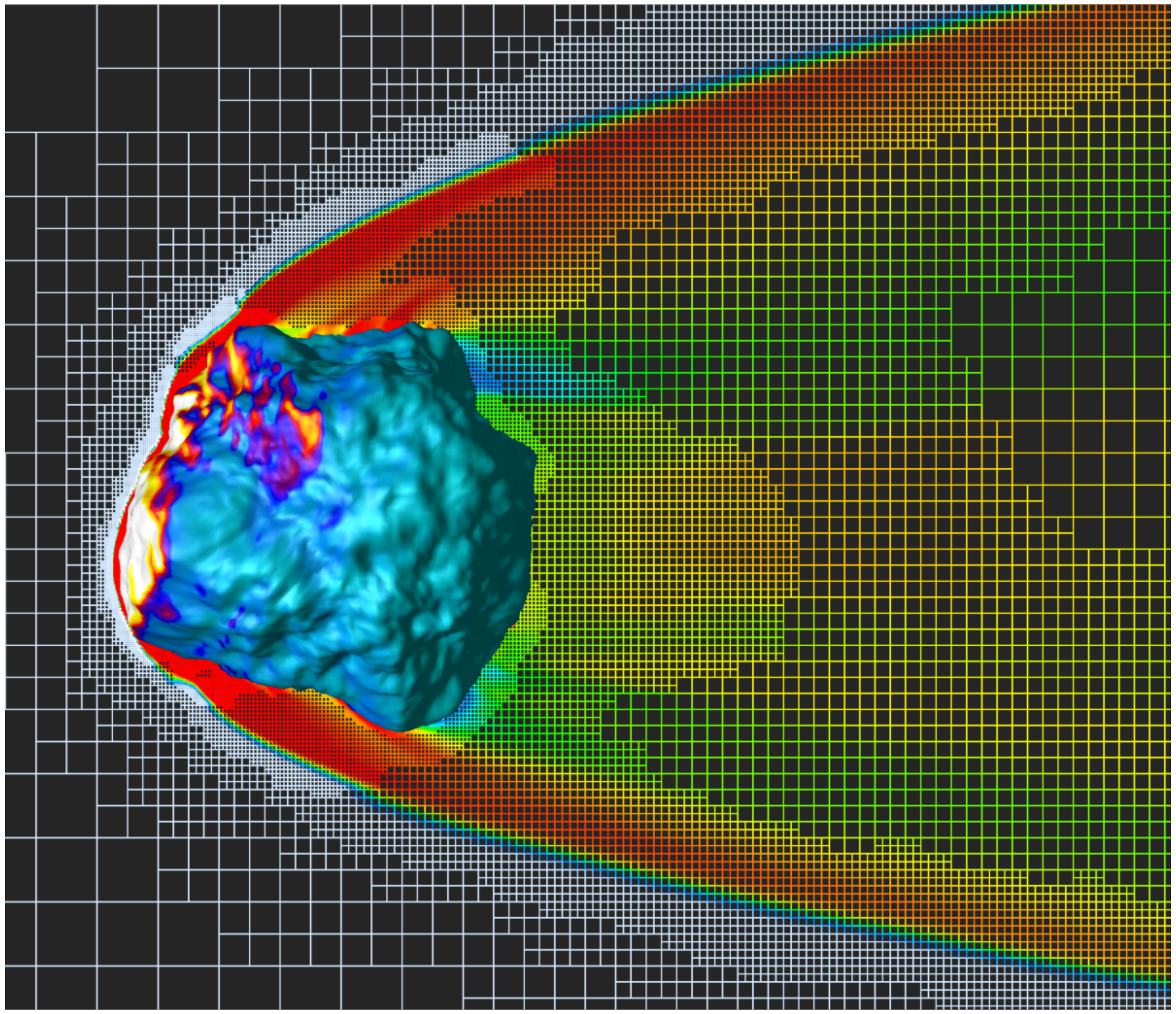
- Rock shape is an arbitrary surface deformation of the sphere
- Examine the influence of shape on pressure signature

Near-body Flow Solutions (M=48)



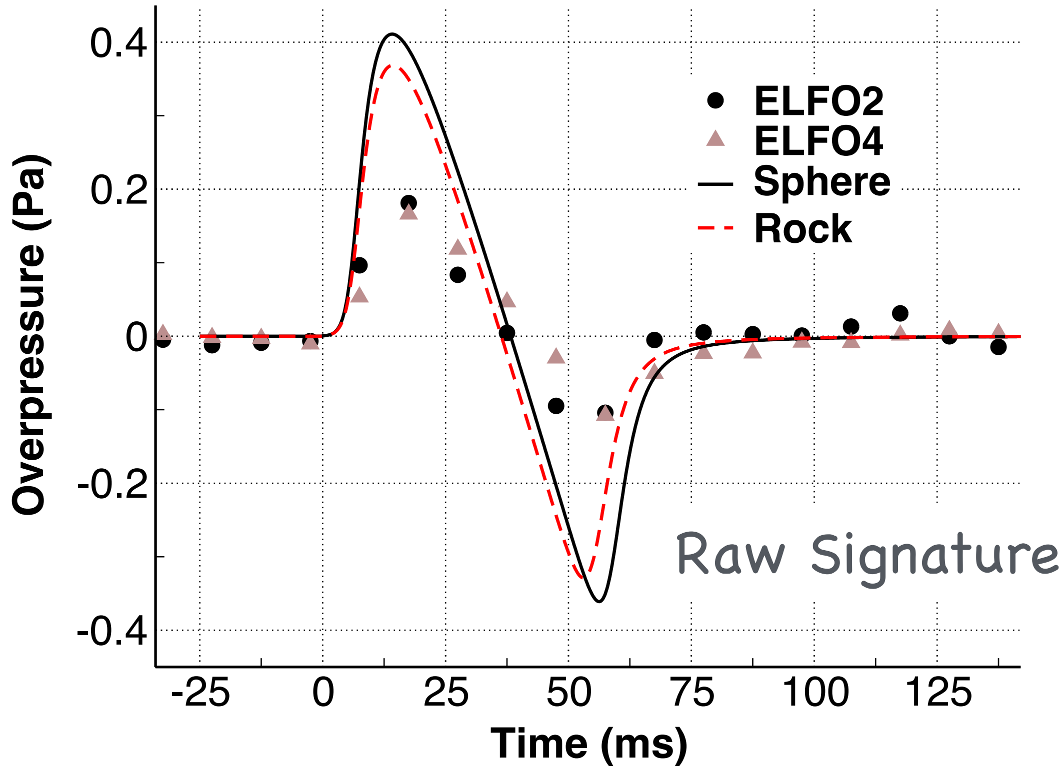
Density Contours

Mesh colored by pressure, body colored by C_p

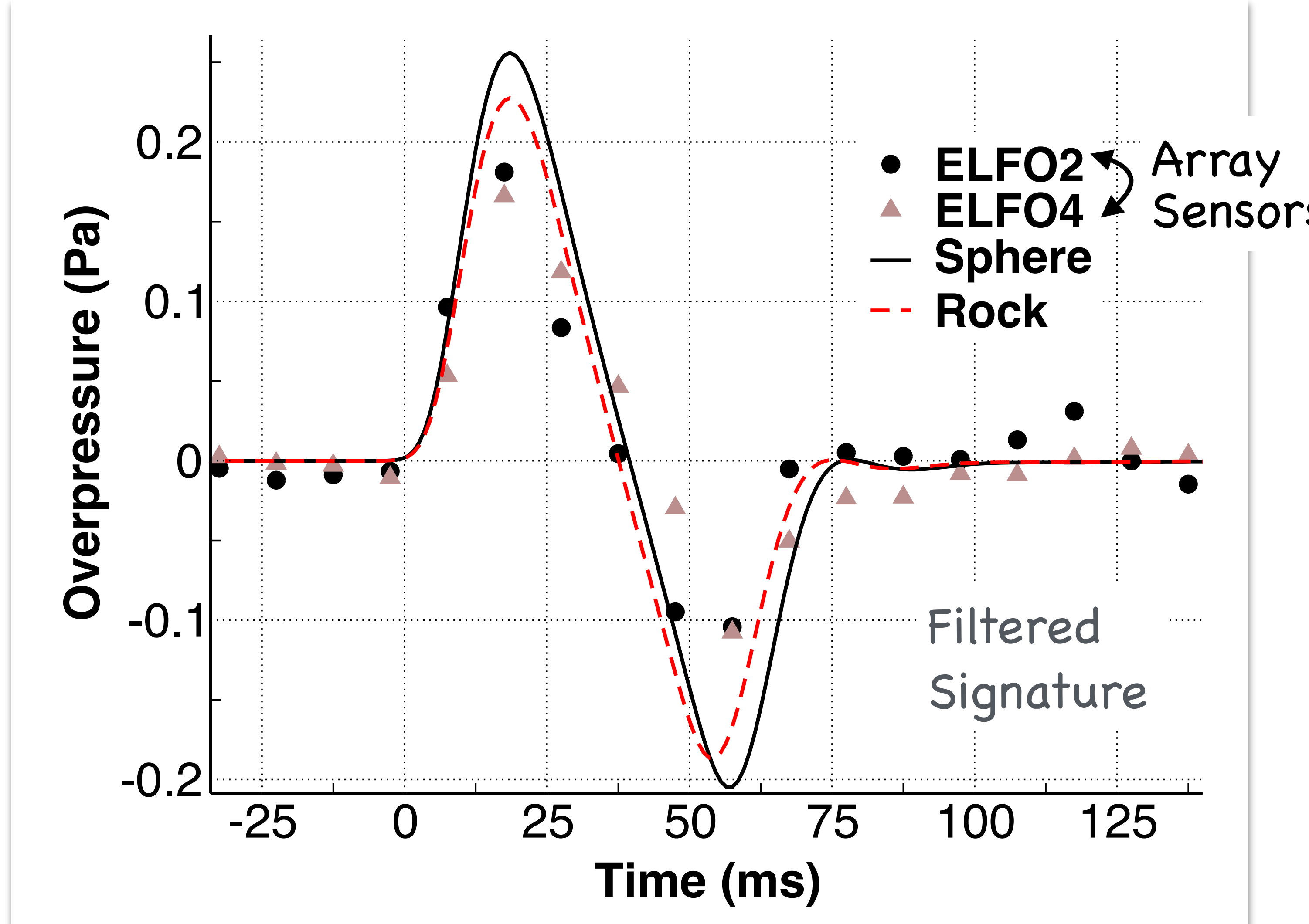


Final mesh size 80-90 million cells

Comparison with SOMN Observations

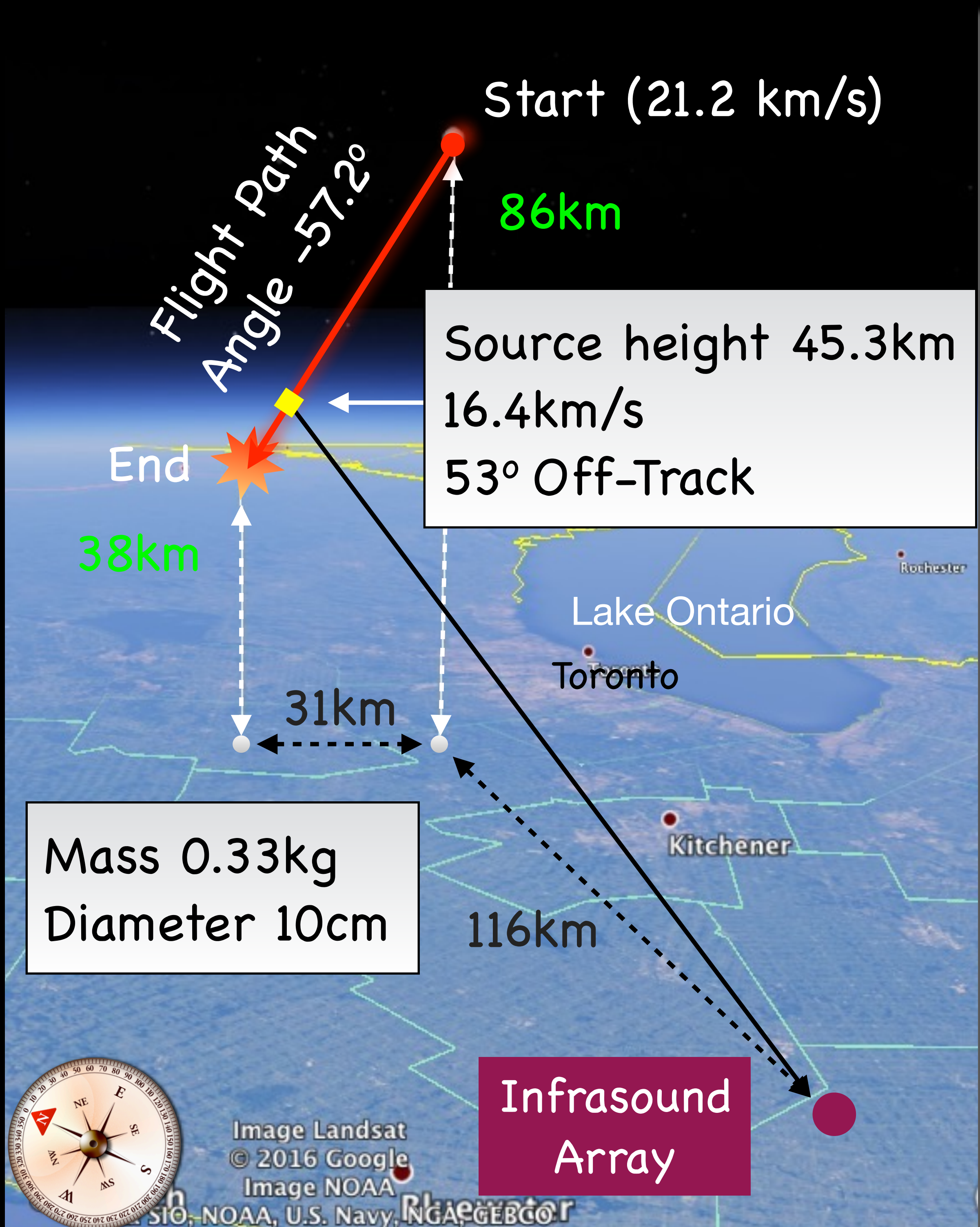


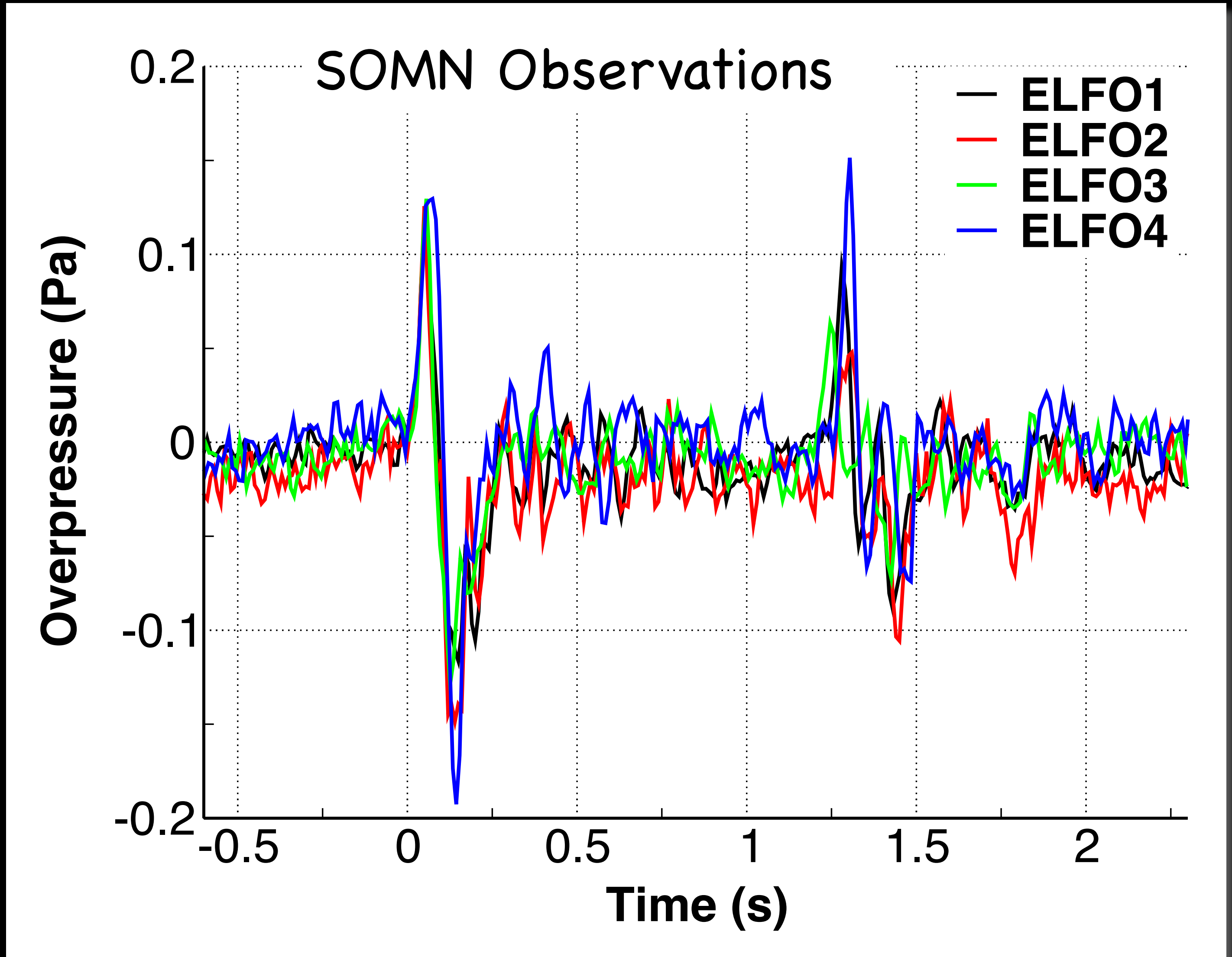
- Observations filtered with 1 Hz high-pass
- Simulation scaled and filtered same as Stardust



- Excellent prediction of rise time, positive-phase duration and period
- Similar over-prediction of zero-peak and peak-to-peak amplitudes as in Stardust
  - Can be slightly improved by including minor deceleration and ablation
- Validates photometric mass estimate!

Meteor 20090428





Sensors show 2 distinct arrivals

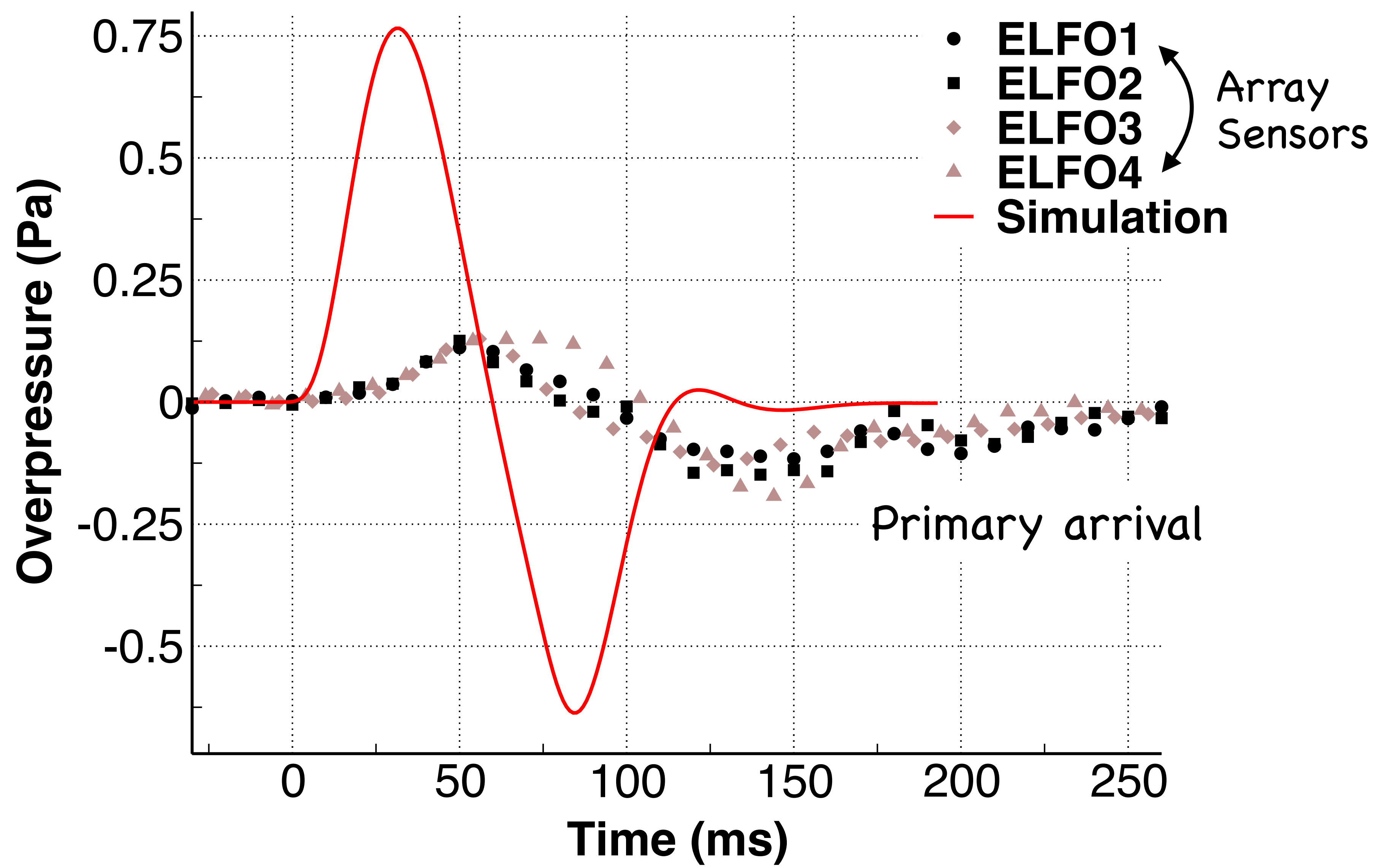
- Assume one is specular while the other is from fragmentation
- Can simulation identify the specular arrival?

Ground Signature from 45.3km (M=50.2)

Flight Path -57.2°

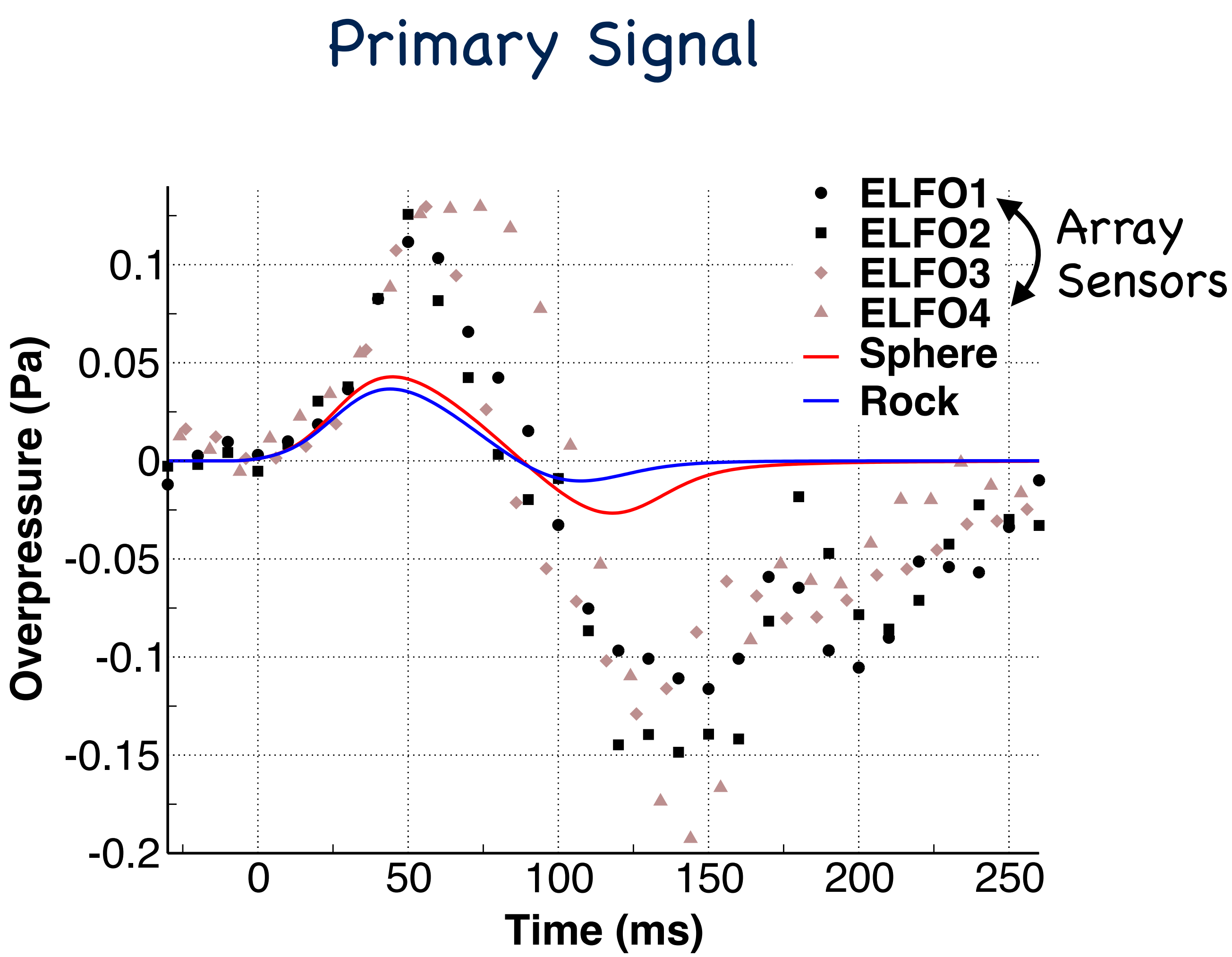
Off-track 53°

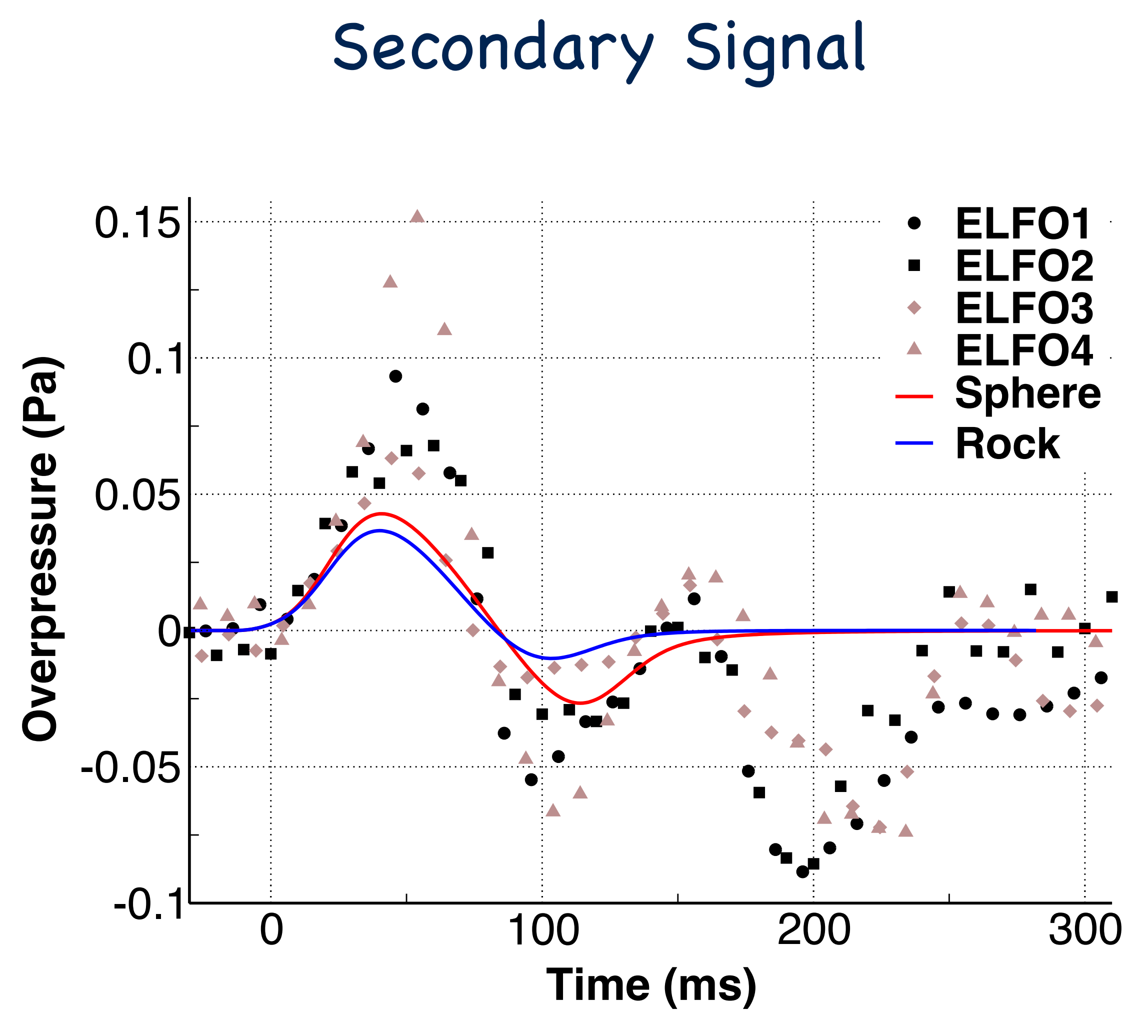
16.4 km/s



- Signature from specular (geometric) source height does not match observations
  - Search higher — 70 and 60 km — to identify source height

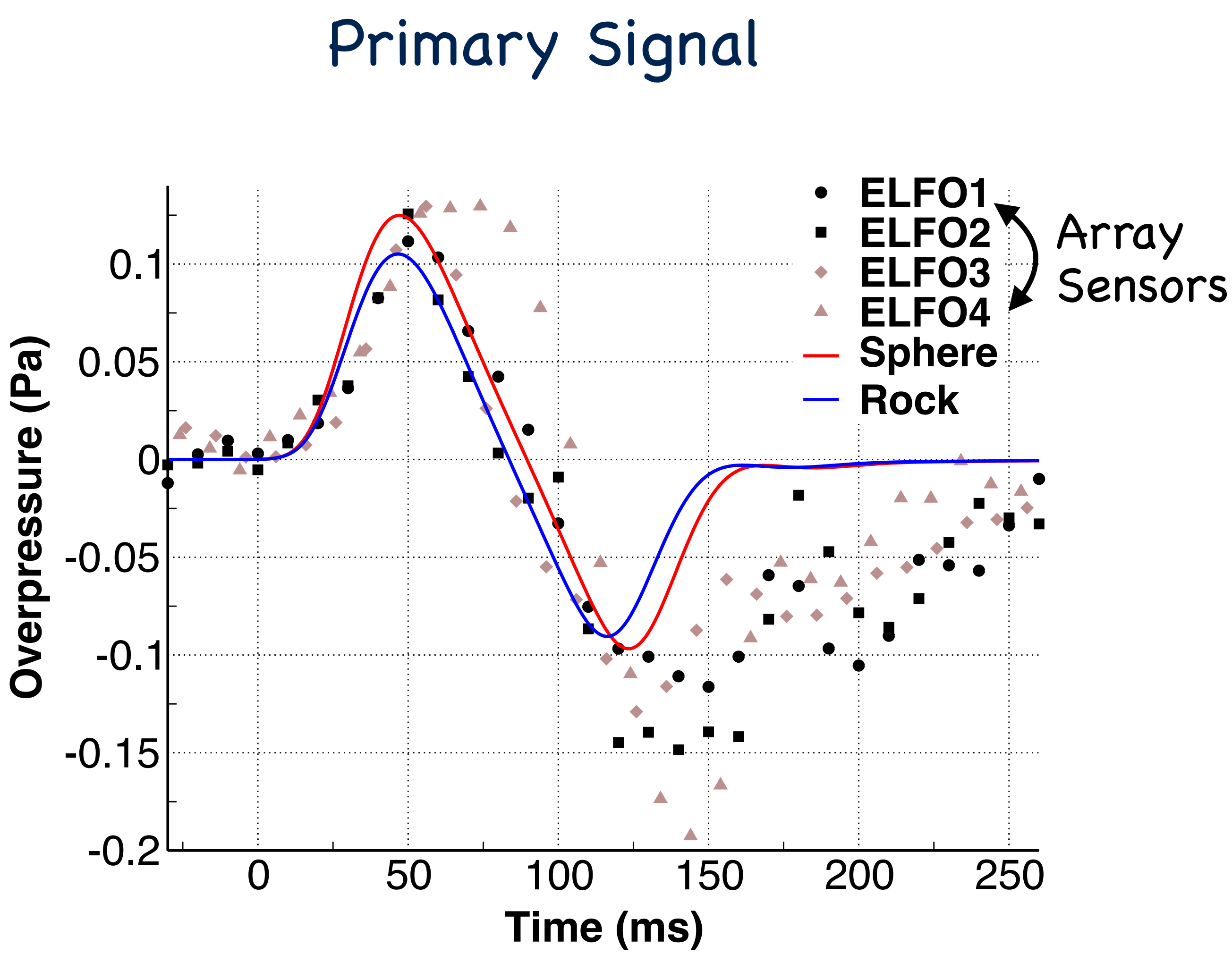
Ground Signature from 70km (M=71.6)

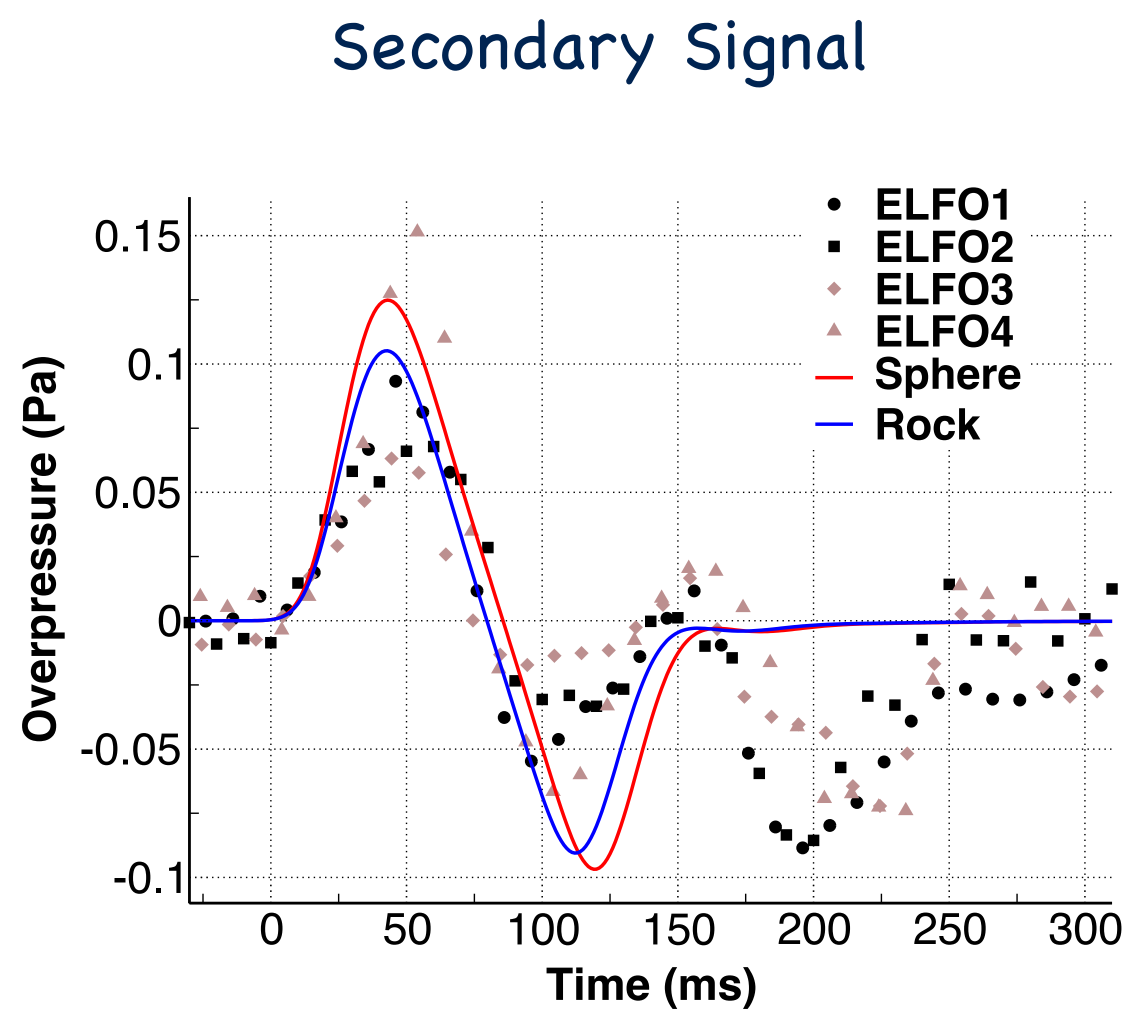




- Positive-phase duration matches both signatures well
- Predicted amplitude is much lower than observations
- 70 km height is too high

Ground Signature from 60km (M=67.1)



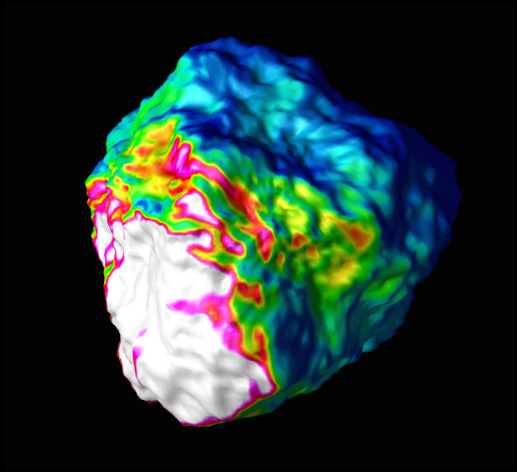


- Rise time and positive-phase duration match both signatures well
- Deep expansion and slow recompression of the primary signal is not captured
- Primary signal: lower altitude fragmentation?
- Secondary signal: higher altitude specular arrival?

Summary

First validation of numerical simulations that predict meteoric pressure signatures

- Stardust entry verified proposed approach
  - Instrument local response remains an open question
- Completed two meteor cases: SOMN 20081028 and 20090428
  - Filtered signatures show excellent agreement in rise time, positive-phase duration and amplitude
- Promising approach to help interpret meteor observations



Acknowledgements

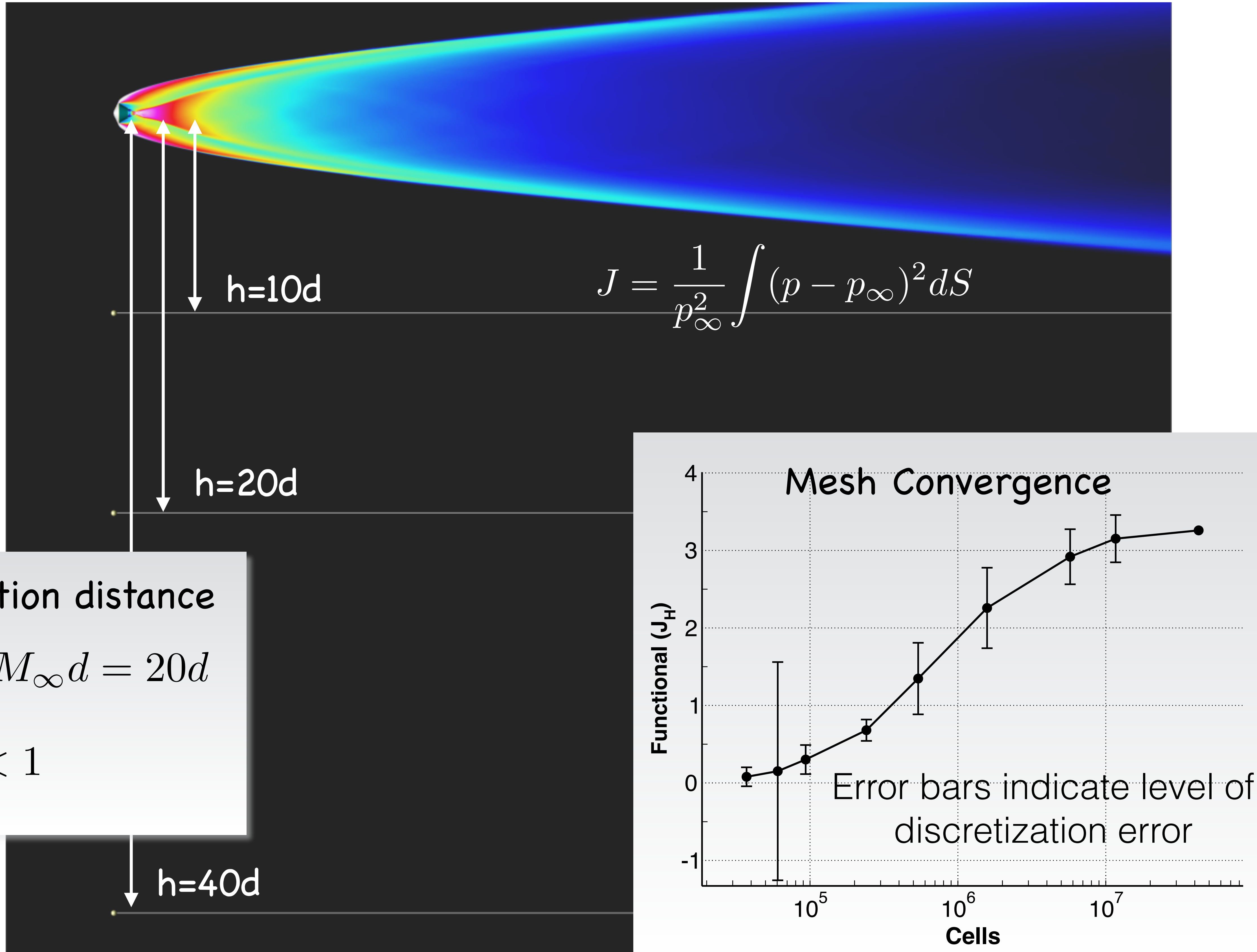
- Asteroid Threat Assessment Project (ATAP) at NASA Ames
- Wayne Edwards (Natural Resources Canada) for Stardust infrasound data
- Russell Franz and Edward Haering (NASA Armstrong Flight Research Center) for Stardust microphone data
- NASA Ames Research Center contract NNA10DF26C

Questions

marian.nemec@nasa.gov

Backup Slides

Pressure Signature Extraction Distances



$$J = \frac{1}{p_\infty^2} \int (p - p_\infty)^2 dS$$

Extraction distance

$$R_0 \approx M_\infty d = 20d$$

$$\frac{\Delta p_s}{p_\infty} < 1$$

Ground Signatures

Microphone Array Location

M 19.4

Speed 6.4 km/s

Off-track 4°

Altitude 50.4 km

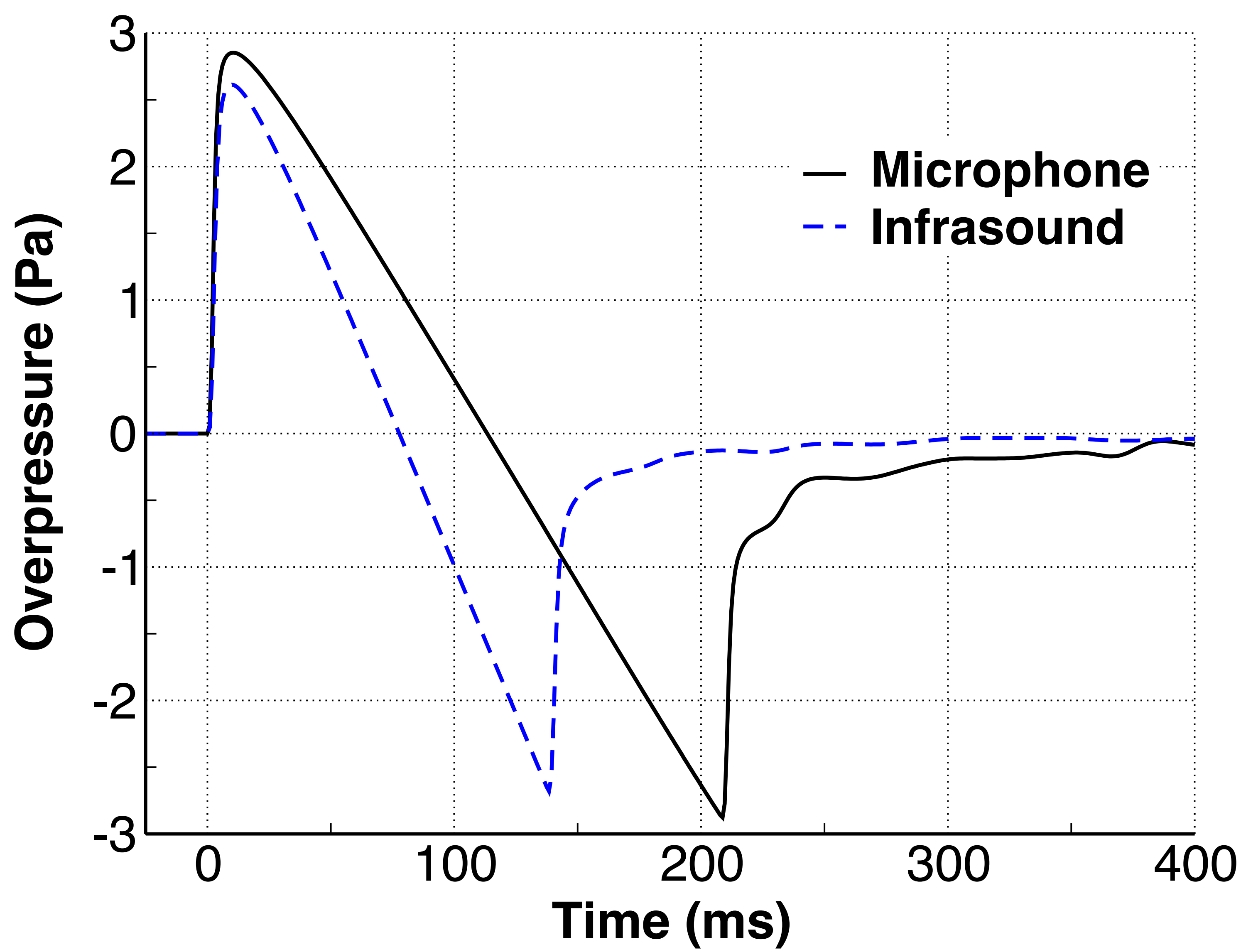
Infrasound Array Location

M 9.5

Speed 3 km/s

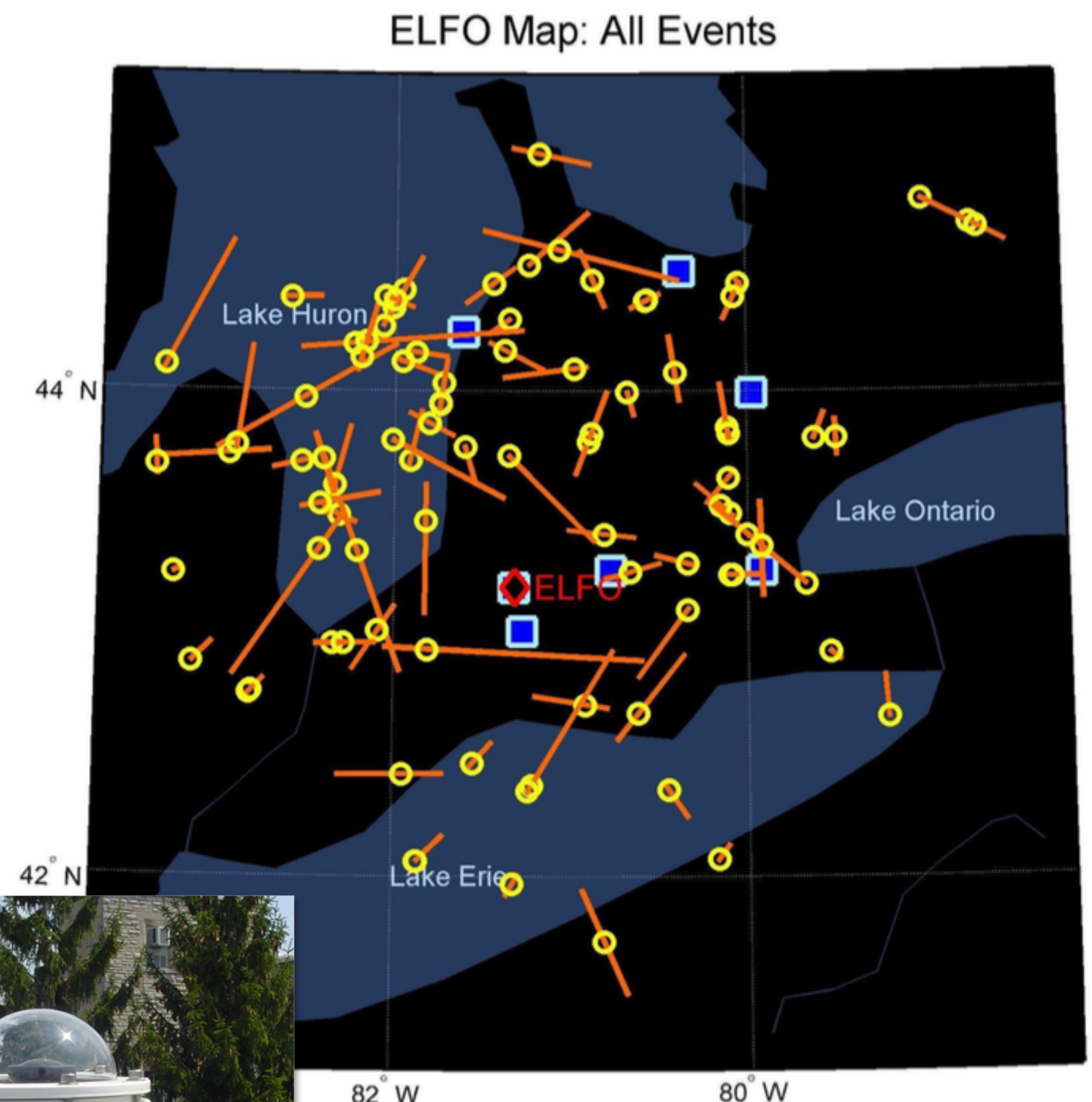
Off-track 38°

Altitude 43 km



Southern Ontario Meteor Network

- Integrated optical and infrasound instruments
  - All-sky camera network (10 stations)
  - Elginfield Infrasound Array (ELFO)
- Between 2006–11: 6,989 meteors with 80 infrasound signatures



Silber & Brown, J. Atmospheric and Solar-Terrestrial Physics, 2014